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ABSTRACT OF THESIS (Regulation 7.9)

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Title of Thesis AGRICULTURAL MACHINERY SELECTION AND SCHEDULING OF FARM OPERATIONS

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The procedure of calculating annual machinery ownership costs from the discounted cash flows of the mortgaged capital cost, the repair and insurance charges and the resale income is extended to include the effect of loan rate and loan period on interest charges, the effect of capital allowances taking account of the actual balancing charges at the end of the period of ownership, and the effect of tax relief on the interest charges, repair costs and insurance premiums. The concept of marginal holding cost is applied to determine the optimum ownership period.

The selection of tractor-plough combinations is based on the prediction of soil characteristics such as moisture content, strength, and workability, all of which influencing the assessment of plough draught and tractor power. A number of filters are used to select the appropriate and realistic tractor/implement combinations with different sizes of fully mounted plough depending on the draught, and the speed of each selected gear of the tractor. For each acceptable combination of tractor and fully mounted plough determined, the costing routine is used to calculate the annual costs.

The branch and bound algorithm is suitable for mixed integer solutions to the farm machinery selection problem. Machinery sets are selected simultaneously with the chosen cropping pattern on a given land area. Machinery sets are matched correctly to the tractor sizes. Four sizes of tractor are available (45 kW, 61 kW, 74 kW and 94 kW). Field operations take place in discrete time periods during which available work days are predicted from soil type and weather records for the specific site. Cereal and root crops are distinguished by optimum sowing and harvesting date. Discrete time periods are defined in relation to these optimal dates and give rise to overlapping operations for different crops. The calculation of probability levels for available work days when operations are subject to different criteria is discussed. A single arbitrary value of 75% probability for available work days is adopted in the linear programming model for the main part of the study.

Two stage processes are used to simulate available work days in each time period. The patterns generated converge on the relative frequency pattern laid down by the generating process. The range of experience is wider than that contained in the short series of 24 years historical data. The simulation model generates results suitable for stochastic dominance ranking.

In a simulation experiment on a 250 ha arable farm cropping cereals and potatoes, alternative solutions are obtained by integer linear programming, the solutions being ranked according to gross revenue. Annual costs of operating farm machinery are derived from a separate costing algorithm based on the annual hours of use which are determined by the size of the task and not by the sequence of work days. After deducting the annual costs of machinery operation, the cumulative net revenue curves cross and second order stochastic dominance ranking is used to identify the optimum (maximum profit) solution.

The current study demonstrates the viability of the analytical procedures but further work is now required to reduce the computing time involved for the complete machinery selection procedure. Meanwhile, a commercial software package is prepared on the calculation of annual machinery ownership costs.

AGRICULTURAL MACHINERY SELECTION

and

SCHEDULING OF FARM OPERATIONS

by

TAHAR SAADOUN

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Presented

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EDINBURGH, SCOTLAND

DEDICATED

TO

MY FAMILY

I hereby declare that all the work presented in this thesis is original and has been carried out by the author unless otherwise stated.

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NOTATION

a	= depth of cut, m;
a_{ie}	= technical coefficient for the ith constraint and the eth activity;
a_p, b_p, c_p	= coefficient of plough price;
a_t, b_t	= coefficient of tractor price;
A	= area, ha;
A_h	= actual throughput, t/h;
A_r	= rated throughput, t/h;
A_t	= present annual cost, £;
b	= tyre section width, m;
b_f, b_r	= front and rear tyre section width, m;
b_i	= resource available in the ith constraint;
B, H	= vertical and horizontal coordinates of application point, m;
B_F, B_R	= front and rear numerics, MN_FW_F, MN_RW_R;
BC	= balancing charge, £;
C	= net capacity of the combine harvester, t/h;
C_i	= price of the eth activity in the objective function, £;
C_r	= clay ratio;
CA	= capital allowance, £;
CF	= cash flow, £;
CFM, CFN	= annual cash flows for two different periods of ownership excluding and including an additional year;
CI	= cone index, kN/m^2;
C_{RR}	= coefficient of rolling resistance;
$(C_{RR})_f$	= coefficient of rolling resistance of the front wheels;
$(C_{RR})_r$	= coefficient of rolling resistance of the rear wheels;
C_T	= coefficient of traction;
$(C_T)_{max}$	= maximum coefficient of traction;
d	= overall tyre dimension, m;
d_s	= distance between field and store, km;
D	= plough draught force, kN;
d_f, d_r	= front and rear wheel diameter, m;
DWC	= dynamic weight coefficient;
FC	= specific fuel consumption, l/kWh;
F, G, E, H_o	= risky prospect functions;
$f(x)$, $g(x)$	= probability distribution functions;
$F_1(x), F_2(x)$, $G_1(x), G_2(x)$	= cumulative distribution functions;
g	= gravitational constant, m/s^2;
h	= tyre section height, m;
h_d	= working hours per day, h/day;

i_i	= investment interest rate, dec;
i_l	= loan interest rate, dec;
I	= annual interest charges, £;
j	= inflation rate, dec;
k	= rate constant at max traction;
k_1, k_2	= resale exponents;
k_c, k_ϕ	= cohesive and frictional coefficient;
k_t	= timeliness coefficient;
k_z	= draught coefficient;
k_{z1}, k_{z2}, k_{z3}	= draught constants;
L_t	= effective load capacity of trailer(s), t;
m_c, n_r	= number of variables and constraints;
M_C	= marginal cost, £;
MN	= mobility number;
M_a	= availability of the machine, dec; (1- decimal of down time);
M_m	= annual mortgage, £;
MN_F	= front wheel mobility number;
MN_R	= rear wheel mobility number;
n	= machine age, yr;
n_c	= cone index exponent;
n_g	= ratio of wagon(s) volume to grain tank volume;
N	= period of ownership, yr;
N_b	= number of plough bodies;
N_t	= number of transport unit;
NPV	= net present value, £;
NPV_m	= present total mortgage cost, £;
NPV_r	= present annual cost of repairs and insurance, £;
NPV_s	= present resale value, £;
NPV_t	= present value of tax deductible allowances, £;
OC	= oil consumption, l/h;
p	= power reserve in tractor, dec;
P	= power required;
P_i	= rated tractor power required (kJ/ha);
PD	= horizontal implement draught, kN;
P_{max}	= rated engine power, kW;
PP	= purchase price, £;
PP_p	= plough purchase price, £;
P_{PTO}	= maximum power take off, kW;
PP_t	= tractor purchase price, £;
Q_D	= torque required to overcome the rolling resistance, kNm;

r = rolling radius of the driven wheel, m;
R = rolling resistance force, kN;
R_{gs} = grain straw ratio;
R_{min} = minimum weight in the risk system;
R_n = annual repair cost, £;
RA, RB = repair constant and exponent;
RU = power utilisation ratio;

s = wheel slip, %;
S = resale value, £;
S_p = operating speed, km/h;
SA, SB = first year correct factor and annual depreciation;

t = marginal tax rate, dec;
t_o, t_a = optimum and actual date of sowing day;
t_L = time for loading, unloading, h;
t_s, t_f = starting and finishing time of an operation, day;
t_w = waiting time, h;
t_1 = loading time of trailer(s), h;
t_2 = unloading time of trailer(s), h;
t_3 = transport time, h;
t_4 = waiting time, h;
t_5 = filling time, h;
t_6 = unloading time of the grain tank into the trailer, h;
T = net available thrust, kN;
T_L = threshing loss, %;
T_{max} = maximum driven wheel thrust, kN;
TAR = total accumulated repair cost, £;

v = velocity, m/s;
V_o, V_1 = optimum and actual operating speed, km/h;

w = inflated discount factor;
w_b = width of furrow, m;
w_1, w_2 = relative weighting system in risk;
W = tyre load, kN;
W_d = proportion of working days to calendar days;
W_e = effective operation width, m;
W_i = plough weight, kN;
W_r = working rate of the machine, ha/h;
W_t = total weight transfer to the rear wheels, kN;
W_{ti} = weight transfer from the implement to the rear wheels, kN;
W_{tt} = weight transfer from the front axle to the rear wheels, kN;
W_F = weight on the front wheels, kN;
W_R = weight of the rear axle, kN;
W_{RS} = static weight on the rear wheels, kN;
WB = wheel base, m

X = accumulated use, h x 10^3;
X_e = eth activity level;
x_h = date of harvesting, day;
x_r = date of ripeness, day;
X_2 = harvesting duration function;

y_i = ith constraint level;
y_s = front end loss, %;
Y = grain yield, t/ha;
Y_L = percentage of field loss, %;

Z = specific draught, kN;
Z_f = objective function, £;
Z_o = quasi-static component of specific draught, kN;

γ = soil specific weight, kN/m^3;
δ = tyre deflection, m;
δ_f, δ_r = front and rear tyre deflection, m;
η_f = field efficiency;
η_T = tractive efficiency;
Θ = soil moisture content, %w/w;
λ = lateral direction angle of the plough, deg;
σ = soil stress factor, kPa;
ϕ = draught angle below horizontal, deg;
π = 3.1415927, 180°;
ρ = coefficient of risk;
α = range of variables between 0 and 1;
Θ_1, Θ_2 = angles of risk system.

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1. INTRODUCTION

As the number, size, complexity and cost of machines increase, the adequacy of machinery management has a major impact on farm profitability. Optimum machinery management is achieved when the overall profitability of the farm business is maximised. This economic goal is not necessarily equivalent to minimising machinery costs for a number of reasons. Different enterprises demand different machine combinations. It may well be the case that optimum utilisation requires area adjustments which are unacceptable for rotational reasons. To reduce yield losses from untimely operations, farmers are tempted to buy big tractors and machines but they do not always consider the economic justification. Several small or medium sized machines and tractors can be more versatile and useful than a single large one, but it is difficult to solve a complicated choice without going through some form of selection and scheduling programs. Selection of farm machinery is one of the most significant tasks facing farmers and managers, because any mistake with cost and investment decisions such as whether to use a machine and which one to use, and whether to buy a machine and which sized machine to buy in order to complete the scheduled job on time, has very serious economic implications. Farm machinery capacity is influenced by the field operations, the weather, the soil conditions, the crop rotation and by the equipment performance. The factorial interaction between these parameters is achieved using some modelling techniques such as a Markov model, simulation model, and linear programming model to find the optimum solution and the most profitable which is determined by the probability distribution of net revenue, Fig 1.1.

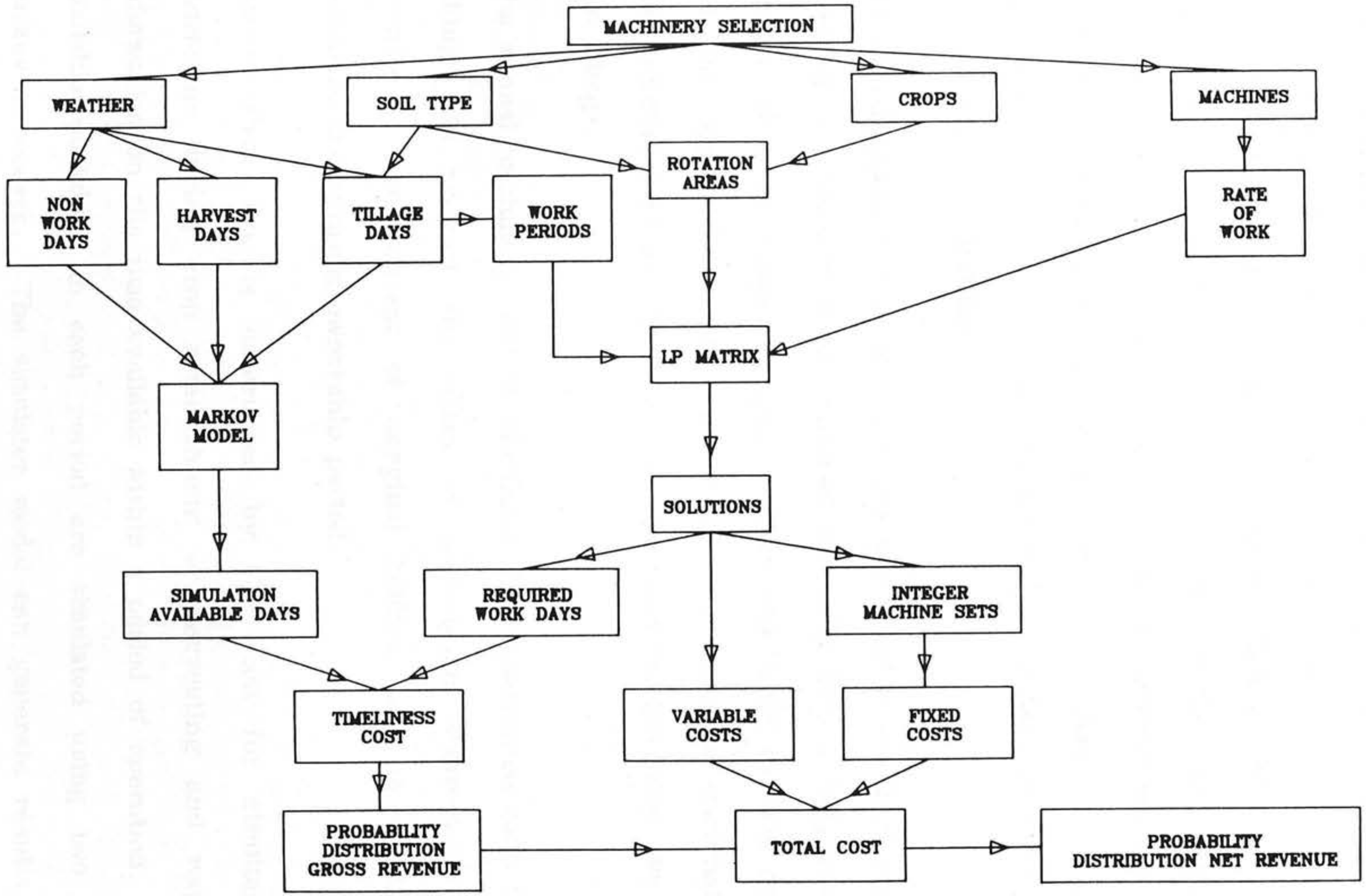

Fig 1.1 Agricultural machinery selection system

The choice of crop rotation and machinery complement requires simultaneous consideration. The objective of the current study is to provide effective machinery management through the scheduling of field operations to identify the fleet size and power mix of tractors and the associated machinery on an arable farm. Scheduling can play an important role in improving efficiency of different operations over the year. The procedure can be used in Agricultural Extension to identify the effect of different tractor and machinery strategy on fixed cost, taking into account the available workdays provided from soil and weather variables.

The initial approach was to select the two wheel drive tractor power level for the primary tillage matched correctly with a fully mounted plough using the number of tractor gears and speed in each gear to get the appropriate and realistic tractor/implement combinations. The optimum cost per hectare was calculated to determine the least cost tillage.

The annual machinery cost is calculated from discounted cash flows, taking into account the effect of decremental depreciation and taxation. The concept of marginal holding cost is applied to determine the optimum ownership period.

Tractor fleet size is determined by the need for simultaneous operations during crop establishment or harvesting and requires information on the time available within a period of operation. The available workdays in each period are simulated using two stage Markov processes. The simulator model can generate results from given historical weather records. The generated information is used in a standard matrix comprising the machinery operation and resource constraints. This matrix is solved by the application of linear programming. In the linear framework, machinery selection is an example of a mixed integer programming problem since some of the variables can only be presented as integers. As many solutions lie close to the optimum, it is useful to introduce other parameters such as timeliness penalties appropriate to the deviation from the optimum dates of sowing and harvesting, or inadequacy of machine capacity which incurs yield penalties from untimely operations. These penalties rely on an assessment of loss in crop yield at harvest associated with establishment at a time period.

The range of solutions are then ranked by means of stochastic dominance. The appeal of stochastic dominance as a technique for appraising risky prospects is that it avoids the difficulty of having to elicit a decision-maker's utility function and provides a general prescription which should suit a broad group of farmers who would qualify on the grounds of some degree of risk aversion. First and second order of stochastic dominance has been used to determine the gross and net income. Sensitivity analysis in stochastic dominance is used as a technique to determine the coefficient of risk aversion that a farmer is willing to have or able to accept.

The relevance of investigations in this study is demonstrated by a combination analysis of an integer linear programming complemented by a simulation programme. The output solution of the integer linear programme is utilised as input data for the cropping simulation model. It is clearly demonstrated in the thesis that the techniques applied in the project are compatible and realistic.

Further investigations should extend the project by including additional activities within crop rotations and to examine the effect of compaction penalties in addition to timeliness.

2. LITERATURE REVIEW

This review examines previous research which is relevant to the development of a whole farm machinery scheduling model. As ploughing is the most draught demanding operation on arable farms, it determines the total tractor power requirement. The need for simultaneous operations identifies the number of tractors in the fleet. Regardless of the size of the individual tractors and machines, they must be correctly matched for economic operation. The selection of tractor/implement combinations is discussed in the first part of the review.

In order to schedule operations economically but without excessive crop losses from untimely operations, data is required on the rates of work of the various sizes of machines, the number of days available for field work, and the extent of the crop losses when work is delayed. Methods of incorporating this information in different types of scheduling models are then discussed.

The development of machinery costing procedures is an essential part of the investigation. In the early stages of the work on tractor/implement combinations, a least cost objective was quite adequate. Once the whole farm model was developed, this minimum cost objective is converted to the more correct maximum profit objective. These two objectives are not necessarily the same because a minimum cost machinery complement may be associated with high crop losses from untimely operations or from excessive soil damage, depending on whether very small or very large machines are selected.

2.1 Selection of tractor/implement combinations

For an effective operation at an economic cost, the plough draught must be correctly matched to the tractor power and must be adjusted to work under a wide range of soil and field conditions. In order to maximise rate of work for a given tractor, it is essential to vary forward speed and number of plough bodies used. The basic selection of tractor/implement combinations for tillage operations can be divided into:

the draught and its effects;
tractor drawbar pull for the implement;
matching a single tractor/plough combination.

2.1.1 Plough draught

Sohne (1960) adapted an equation which was developed and used by Goryachkin (1940) to show the interdependence between the draught and speed of tillage in the following form:

$$Z = Z_o + k_z v^2(1 - \cos \lambda) \qquad \ldots\ 2.1$$

where
Z = specific draught, kN;
Z_o = quasi-static component of specific draught; kN;
v = velocity, m/s;
λ = lateral direction angle of the plough, deg;
k_z = coefficient constant.

The same shape of equation was used by Voorhees and Walker (1977) to determine the effect of soil moisture content, Θ, on the quasi-static draught component, such that:

$$Z = k_{z1} + k_{z2}\Theta + k_{z3}v^2 \qquad \ldots\ 2.2$$

where
Z = specific draught, kN;
k_{z1}, k_{z2}, k_{z3} = coefficient constants;
v = velocity, m/s;
Θ = soil moisture content, % w/w.

Gee-Clough et al. (1978) extended the work by using field data. They developed an empirical plough draught equation based on the dimensionless formula modelled by Krastin (1973):

$$\frac{D}{a^2\sigma} = f\left(\frac{w_b}{a}, \frac{\gamma a}{\sigma}, \frac{ga}{v^2}\right) \qquad \ldots\ 2.3$$

where D = plough draught force, kN;
g = gravitational constant, m/s^2;
a = depth of cut, m;
w_b = width of cut, m;
γ = soil specific weight, kN/m^3;
σ = soil stress factor.

However, it was argued later that the draught depends only on soil specific weight and this empirical statement simplified Krastin's equation to the following form:

$$Z = 13.3\,\gamma a + 3.06\,\gamma v^2/g \qquad \ldots\ 2.4$$

Eradat Oskoui and Witney (1982) proposed a form of the plough draught equation which is a combination of the quasi-static draught component using Coulomb's soil strength theory with cone index values substituted for the cohesive and frictional parameters and a dynamic component which incorporates the effect of tail angle. They mentioned that cone index is a function of soil moisture content and soil specific weight which jointly represents the cohesive and frictional components of the penetration resistance such that:

$$CI = f(c) + f(\gamma) \qquad \ldots\ 2.5$$

There is practical validity for the assumption that the quasi-static component of plough is a function of cone index. The plough draught equation was remodified by taking into account the effect of mouldboard tail angle on the dynamic component of plough draught.

The general form of the plough draught equation becomes:

$$D = [0.050\ CI + (9.66\gamma\, v^2(1 - \cos\lambda)/g]\ a w_b N_b \qquad \ldots 2.6$$

where D = plough draught, kN;
CI = cone penetration resistance, kPa;
γ = soil weight, kN/m^3;
g = gravitational constant, m/s^2;
v = velocity, m/s ;
a = working depth, m;
N_b = number of plough bodies;
w_b = furrow width, m;
λ = ploughing tail angle, deg.

Further investigations of cone index were made by Witney et al. (1984). As the clay fraction has cohesive properties by virtue of its chemical bonds, it was concluded that the ratio of clay to silt and sand, C_r, could be used as a practical monitor of soil type which could be part of the cone penetration resistance equation. Elbanna and Witney (1987) developed a cone index equation in which they proposed that the tangent of the angle of internal shearing resistance was related to an inverse function of the clay ratio. The cone index equation took the form:

$$CI = \{k_c C_r \exp[-n_c\Theta/(1+C_r)] + k_\phi\gamma/(1+2C_r)\}\exp[\pi/(1+2C_r)] \qquad \ldots 2.7$$

where C_r = clay ratio;
k_c and k_ϕ = cohesive and frictional coefficients;
n_c = exponent;
Θ = soil moisture content, % w/w.

The objective of these investigations was to determine the relationship between shearing resistance through the penetration of a cone, clay ratio, soil moisture content and specific weight to generate part of the draught equation.

Bainer et al. (1965), Hunt (1974a), and Collins et al. (1978) concluded that the relation between unit draught and speed for mouldboard ploughs tends to increase with speed. Summers et al. (1984) also concluded that plough draught is a linear function of speed for chisel ploughs, discs and sweep ploughs, but a quadratic for mouldboard ploughs and varies linearly with depth for all tillage implements. The effects of ploughing depth, soil density, travel speed, and coefficient of soil mouldboard friction on predicted draught were studied by Gao et al. (1986). They developed a pure mathematical model to predict soil forces on the plough mouldboard. They concluded that the predicted draught was proportional to soil density and ploughing depth and was a quadratic function of travel speed. Their results are in agreement with the experimental work of Eradat Oskoui and Witney (1982).

2.1.2 Drawbar pull

The moisture content of soil affected the draught of cultivating tools, each soil having a minimum resistance at one specific moisture level. Ploughing period is limited by the acceptable moisture content of the soil and the time of sowing. It is impossible to wait indefinitely for periods during which it is suitable for ploughing to make a better job. The answer can be given by the following methods:

(a) use a large number of ploughs and tractors,
(b) use a large plough by increasing the number of bodies,
(c) increase the plough speed,
(d) use a large plough at a high speed.

The first method is uneconomic because all the tractors would not be used properly for the rest of the year. A larger plough has a greater output at a given speed, but demands a larger powered tractor which is inefficient for the other operations. The variation in depth of work could be greater with a wider plough, but Barnes and Link (1959) suggested that there is an optimum working width for each type of implement. Bowers (1980) stated that the amount of tractor power lost at the soil type interface can vary from 37% on firm land to 52% on a soft soil. Power loss on a tilled soil can be as much as 44.6%. Assuming that the drive wheel dimensions were kept constant, tractor weight must vary to obtain a constant drawbar pull from a given tractor at a given slip on different soils. According to Zoz (1974b), the rate of work of a 2 furrow plough can be increased by 50% either by converting the plough to 3 furrows or by increasing its speed by 50%. In the first case, it needs a 50% more powerful tractor weighing and costing 50% more. In the second case, a tractor having 60% more power but only 10% more weight will be sufficient to do the job.

The use of the mounted plough is universal for small to medium sized tractors; the power of the tractor can be more efficiently used and wheel slip is decreased. There is a very close proportionality between the engine power of a tractor and a size of the implement. To increase the rate of ploughing, the weight of the tractor has to be increased in order to develop adequate drawbar pull. The same rate of work may be achieved either by pulling a wide implement at low speed or a narrower implement at a higher speed. Thus, agricultural tractors must be designed to convert their available power into drawbar power as efficiently as possible and within an acceptable range of drawbar pull and speed (Dwyer, 1978).

2.1.3 Tractor performance

Zoz (1972) stated that the weight from the implement and from the front tractor axle to the rear axle can be expressed as:

$$W_{ti} = PD \tan \phi \qquad \ldots 2.8$$

$$W_{tt} = PD \left[\frac{H}{WB} + \frac{(B)}{(WB)} \tan \phi\right] \qquad \ldots 2.9$$

$$DWC = \left[\frac{H}{WB} + \left(1 + \frac{(B)}{(WB)}\right) \tan \phi\right] \qquad \ldots 2.10$$

$$W_{t} = PD.DWC \qquad \ldots 2.11$$

where

- PD = horizontal implement draught, kN;
- DWC= dynamic weight coefficient;
- W_{ti} = weight transfer from the implement to the rear wheels, kN;
- W_{tt} = weight transfer from the front axle to the rear axle, kN;
- W_{t} = total weight transfer to the rear wheels, kN;
- ϕ = draught angle below horizontal, deg;
- B,H = horizontal and vertical co-ordinates of application point;
- WB = wheelbase, m.

Wismer and Luth (1973) utilised a clay number and developed a series of equations to predict the coefficient of traction (pull/weight) and tractive efficiency (output pull/input torque). Using his own experiment data, Zoz (1972) adapted the same process to generate a tractor performance chart which was later reproduced by Bowers (1980) in his machinery selection programme. Zoz (1972) quoted that the curves within each soil represented typical weight transfer conditions for the implement; the dynamic weight coefficients being integral hitch type (DWC = 0.65), semi-integral type (DWC = 0.45) and towed (DWC = 0.25) (Fig 2.1). In 1974, he matched tractors and implements on the basis of the implement draught requirements and tractor pull capability. He optimised the travel speed with respect to the power constraints and productivity and produced a graphical solution technique for two-wheel drive tractors. Data needed were actual travel speed, axle load, engine power, type of hitch and soil condition (Fig 2.1). This predictor was reported valid only for steady-state performance of two-wheel drive tractors. Gee-Clough et al. (1977 and 1978) developed a procedure based on Zoz's study (1974b), but they also suggested that the tractive efficiency should be included as an important constraint in tractor implement combinations. They calculated the drawbar power developed by the tractor and the draught requirements of the plough by using an empirical equation (Eq 2.4). Although moisture content significantly affects the tractive performance of the tractor operating on agricultural soils, its omission by Zoz (1972, 1974a, 1974b) was later corrected by others (Wismer and Luth, 1973; Voorhees and Walker, 1977; Gee-Clough, 1980; Eradat Oskoui and Witney, 1982; Eradat Oskoui et al. 1982).

Dwyer et al. (1974,1975) used Turnage's (1972) equation on mobility number which is an extension of Freitag's (1965) work to examine the results of tractive performance tests on tractor drive wheel tyres. Thus, the mobility number, MN, was defined as:

$$MN = \frac{CI\ bd}{W} (\delta/h)^{\frac{1}{2}} \frac{1}{(1 + (b/2d))} \qquad \ldots\ 2.12$$

where MN = mobility number;
CI = cone index, kN/m^2;
b = tyre section width, m;
d = overall tyre dimension, m;
h = tyre section height, m;
W = tyre load, kN;
δ = tyre deflection, m.

It was found empirically that there is a relationship between wheel mobility number and tractive performance parameters, such as rolling resistance, weight, etc. Tyre performance was predicted using cone index in ploughed and cultivated fields from the following empirical equations (Dwyer et al. 1974, 1975; Gee-Clough, 1976, 1978, 1980):

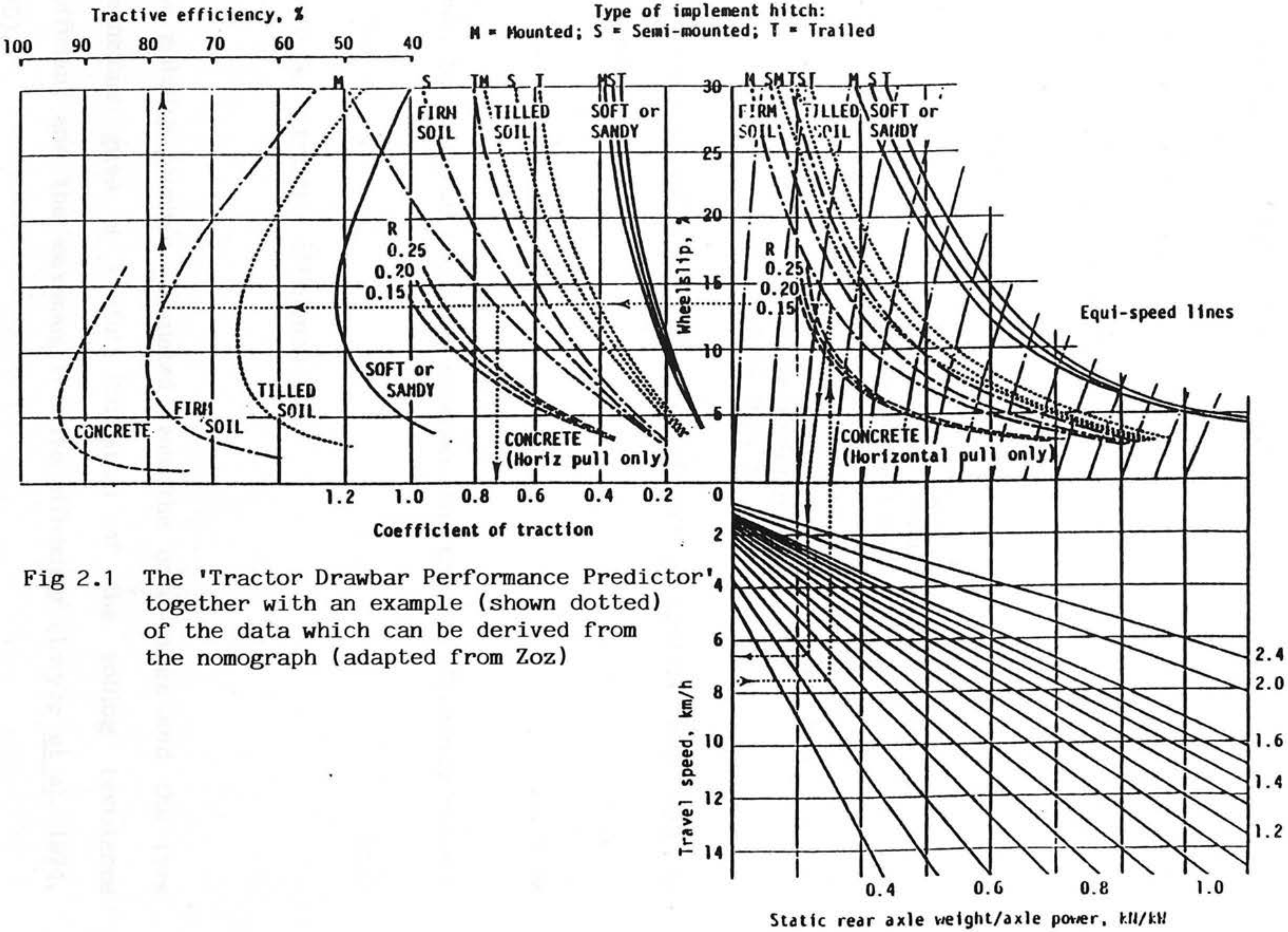

Fig 2.1 The 'Tractor Drawbar Performance Predictor' together with an example (shown dotted) of the data which can be derived from the nomograph (adapted from Zoz)

$$C_T = \frac{T}{W} = (C_T)_{max} (1 - e^{-ks}) \qquad \ldots 2.13$$

$$(C_T)_{max} = \frac{T_{max}}{W} = 0.796 - \frac{0.92}{MN} \qquad \ldots 2.14$$

$$k(C_T)_{max} = 4.838 + 0.061MN \qquad \ldots 2.15$$

$$C_{RR} = \frac{R}{W} = 0.049 + \frac{0.287}{MN} \qquad \ldots 2.16$$

$$s = 9 + 19/MN \qquad \ldots 2.17$$

where C_T = coefficient of traction;
C_{RR} = coefficient of rolling resistance;
$(C_T)_{max}$ = maximum coefficient of traction;
T = net available thrust, kN;
k = rate constant at maximum traction;
T_{max} = maximum driven wheel thrust, kN;
R = rolling resistance force, kN;
s = wheel slip, %.

The proportionality of tractive efficiency against slip can be expressed by:

$$\eta_T = \frac{C_T (1 - s)}{C_T + C_{RR}} \qquad \ldots 2.18$$

Then, by using an empirical equation, the tractive efficiency became:

$$\eta_T = 78 - \frac{55}{MN} \qquad \ldots 2.19$$

where η_T = tractive efficiency.

The mobility number calculated from the cone index and the tyre dimensions gave a useful indication of the rolling resistance coefficient and the maximum tractive efficiency (Dwyer et al. 1974, 1975).

Dwyer (1984) modelled tractor performance by extending the work of Gee-Clough (1980). The thrust from the driving wheels can be developed from the drawbar pull plus the rolling resistance from equation 2.13. He demonstrated that the weight can be transferred from the front axle to the rear axle due to the required torque to counteract the rolling resistance of the undriven wheels. In his study, Dwyer (1984) assumed that the thrust from driving wheels, the implement draught force and the rolling resistance of the undriven wheels do not affect the weight distribution between the axles of a tractor since they react in the same horizontal direction.

The weight on the rear axle, W_R, is then given by:

$$W_R = W_{RS} + \frac{Q_D}{WB} \qquad \ldots 2.20$$

where W_{RS} = static weight on the rear wheels, kN;
Q_D = torque required to overcome the rolling resistance of the driving wheels, kNm;
WB = tractor wheelbase, m.

For a two-wheel drive tractor:

$$W_R = W_{RS} + [W_R(C_{RR})_r]\frac{r}{WB} \qquad \ldots 2.21$$

where $(C_{RR})_r$ = coefficient of rolling resistance of the rear wheels;
r = rolling radius of the driving wheel.

For a four-wheel drive tractor:

$$W_R = W_{RS} + [W_F(C_{RR})_f + W_R(C_{RR})r]\frac{r}{WB} \qquad \ldots 2.22$$

where W_F = weight on the front wheels, kN;
$(C_{RR})_f$ = coefficient of rolling resistance of the front wheels;
W_R = weight on the rear wheels, kN.

However, Dwyer (1984) indicated that the weight transfer from the implement to the rear axle was equal to the implement weight which is added to the tractor weight to represent the total recommended weight on the tractor. The plough weight (conventional mounted) was calculated by empirical equation of the form (Rackham, 1985):

$$W_i = [7.77 + (147.86\ N_b)]g/1000 \qquad \ldots\ 2.23$$

where N_b = number of plough bodies;
g = gravitational constant, m/s^2;
W_i = plough weight, kN.

By using the tractor implement model developed by Dwyer (1984) to generate the dynamic load on the rear axle of the tractor, W_R, Elbanna (1986) extended the same work by substituting all terms in the mobility number other than the wheel load by single terms B_F and B_R for the front and rear wheel respectively, such that:

$$MN_F = \frac{B_F}{W_F} = \frac{CI\ b_f d_f}{W_F}\frac{(\delta_f)^{1/2}}{(h_f)} \quad \frac{1}{1 + (b_f/2d_f)} \qquad \ldots\ 2.24$$

$$MN_R = \frac{B_R}{W_R} = \frac{CI\ b_r d_r}{W_R}\frac{(\delta_r)^{1/2}}{(h_r)} \quad \frac{1}{1 + (b_r/2d_r)} \qquad \ldots\ 2.25$$

Then the rear wheel load equation became:

$$W_R = W_{RS} + W_R\ [0.049 + \frac{(0.287)}{B_R}\ W_R]\ \frac{r}{WB} \qquad \ldots\ 2.26$$

After developing each term, the equation took the final form:

$$W_R = (-(0.049\frac{d_r}{2WB} - 1) - [(0.049\frac{d_r}{2WB} - 1)^2 - 2(0.287\frac{d_r}{WB}W_{RS})]^{1/2}) / (0.287\frac{d_r}{B_R WB})$$

B_F = $MN_F W_F$
B_R = $MN_R W_R$
d_r = rolling diameter of driven wheel (2r), m;
MN_F = front wheel mobility number;
MN_R = rear wheel mobility number;
W_{RS} = static load on the rear axle, kN;
W_R = dynamic weight on the rear axle, kN.

In practice, it may be useful to add ballast in front for stability of the tractor because of the effect of drawbar force of the plough acting on the rear wheels and reducing the load on the front wheels of the tractor. The dynamic load distribution on the front wheels is assumed to be 35%, 42% and 60% of the total weight of two-wheel drive, four-wheel drive (unequal) and four-wheel drive (equal) tractors, respectively.

The dynamic weight transfer from the implement to the rear axle was equal to the implement weight and included with tractor weight to represent the total weight. This is applied only for fully mounted plough. No further investigation has been done for semi-mounted or trailed types and the problem still remains unsolved.

2.1.4 Power requirement for field operations

One of the most important steps in machinery management is to have ample tractor power to perform critical operations on time. The choice of the tractor power level depends on the type of work and the conditions under which it has to be done, and the size of the equipment with which the tractor will be used. Hughes et al. (1977) determined the power required to perform the different jobs under particular conditions. However, power can be modified by changing some controllable factors, such as daily work hours of the tractor and extension of the working period.

ASAE (1982) provided draught and power requirement prediction formulas for tillage tools in different soil types. Draught characteristics of an operation depend on the size, shape and spacing of the soil engineering parts, depth and speed of the operation, and the strength of the field soil. Gunderson et al. (1981) studied two specific tillage implements in which draught, speed, depth and fuel consumption were measured during field operations. Field experiments by Fornstrom and Becker (1977) indicated a large variation in field power requirements and machine performance when using the same condition in field tasks. Pascal and Sharp (1984) measured the tractor power consumption in the field by using an exhaust gas temperature system. This method of power measurement determines the total output power to operate both the tractor and implement. It is difficult for a farmer to achieve optimum performance during field operations because of variations in tractive efficiency. It is very important to know if a machine is underutilised or overused because the farmer could face large penalties in time of operation and specific fuel consumption. Matching of machine width and tractor power has an important effect on time and fuel requirements per unit of land. Better use of engine output is a major factor in controlling agricultural production costs. The objective must be to maximise fuel efficiency and to minimise field time without overloading the engine. Dwyer (1985) reviewed the power levels required for different field operations related to rate of work. Power requirements for transport operations are low compared with requirements for tillage and harvesting. He quoted that, in general, the energy requirement for an arable farm has not changed much over the years, but it is essential to analyse the variation of changes to ensure adequate reserve power under different conditions. Dwyer (1985) mentioned also that fuel consumption is a better way of analysing energy requirement. Matching a large tractor and a big implement saves time but small equipment with a small tractor operating for a long period of time consumes less fuel per hour. Table 2.1 shows the energy requirement for different operations.

The transport requirements in agricultural enterprises differ from

Table 2.1 Mean energy requirements for different field operations (Dwyer, 1985)

Operation	Energy requirement, kWh/ha
Ploughing	70
Subsoiling/Moling	60
Forage harvesting	40
Rotary cultivating	40
Cultivating	30
Disc harrowing	30
Mowing	25
Drilling	20
Hoeing	20
Spring tine harrowing	20
Dutch harrowing	15
Rolling	15
Baling	10
Tedding	10
Spraying	5
Fertiliser distributing	5

other activities by having a higher rolling resistance which requires extra power to move the heavy equipment over soft field surfaces. The power requirements for farm operations are related to the rate of work; the higher the rate of work, the greater the engine output needed to satisfy the requirements.

Wu et al. (1986) divided the equipment requirements in two categories; first was that for ploughing, cultivating and planting, and the second was for harvesting. The optimum width of a given crop establishment implement varies linearly with tractor power depending on different field jobs. When power was fully used for harvesting operations, the time and fuel requirements per unit of area decreased at a declining rate as the machine width increased.

Dwyer (1985) showed a relationship between the power required for transport and the rate of harvesting, the distance from the harvester to the store and the coefficient of rolling resistance of the ground surface. For a rate of harvesting of 12 t/h, a journey of 1 km to the store and a rolling resistance on a stubble field of 0.1, the power required would be 10 kW which was determined by the following equation:

$$P = 8.4\ R W_r d_s \qquad \ldots\ 2.27$$

where P = power required, kW/t;
R = rolling resistance coefficient;
W_r = rate of harvest, t/h;
d_s = distance between field and store, km.

The power required by each implement is also determined using the following equation (Anderson, 1985):

$$P_i = \frac{1}{2.5}\ \frac{1.171\ D}{\eta_f \eta_r\ (1-p)} \qquad \ldots\ 2.28$$

where P_i = rated tractor power required (kW/ha/h);
D = implement draught (kN/m);
η_F = field efficiency (decimal);
η_T = tractive efficiency (decimal);
p = power reserve in tractor (decimal).

2.2 Selection of self propelled harvester-transport combinations

In practice, the effectiveness of a mechanisation policy is determined by the management skill of the work organisation and matching the output of the power and machinery system to the time available at an acceptable level of operating costs. The annual cost surcharge of an over-investment in tractors and machines should be balanced by the timeliness penalties. Before making any decision to apply a method in field machinery management, farm machinery selection has to be done in order to determine field capacity and efficiency of machines used.

2.2.1 Rate of work for harvester

There are two categories of work rate:

theoretical area capacity or spot rate is the rate of performance obtained if a machine is performing for 100% of the time at its operating speed, using 100% of its width but this definition ignores completely field efficiency;

the overall rate of work is the performance of a machine over the complete operational cycle (productive work time plus routine interruptions for turning and product handling).

Field efficiency is the ratio of the overall rate of work to the spot rate of work expressed as a percentage. Field efficiency is undoubtedly the most elusive factor for estimating the field capacity of a farm machine. It is a ratio of actual productivity to its theoretical productivity. It takes into account the lost time resulting in failure to consistently utilise the full operating width of the machine, along with time losses coming from operator inefficiency, operating practices, and field crop or weather limitations. The following items account for the majority of lost time in the field:

- turning at row ends,
- manoeuvring around field,
- idle travel,
- materials handling (unloading unharvested crops..),
- cleaning (sieves),
- making adjustment or minor repairs,
- lubricating and refueling,
- waiting for transport units.

Many factors affecting field efficiency could be under the operator's control. Many others are management problems and can be corrected by the operator. Improving the field efficiency of an operation can achieve tremendous savings for a farmer. A rate of machine performance is expressed in terms of quantity per unit time. Most of the agricultural machine performance is given as area per hour. Sometimes, harvesting is calculated as tonnes per hour.

The time efficiency is a ratio of time a machine is operating effectively to the required time of an operation. Any time the machine is not operating is wasted.

The rates of work used by Donaldson (1970) were obtained from survey diaries kept by a sample of 55 farmers in Kent and East Sussex, with the rates of work being recorded in 132 fields over three consecutive years. The rates of work achieved include the stopping time for machine adjustment and other purposes and are further affected by the skill of the operator.

Donaldson (1970) quoted that the work rate depends on three major factors; physical factors, biological factors and environmental factors.

- Physical factors of both the machine and the operating systems. The wider the machine cutting width, the higher the rate of work expected. Also the rate varies according to the forward speed selected to operate effectively. The rate of work could be affected also by the service, maintenance and repairs required during an operation.
- Biological factors of the crop which depend on difference between crops and varieties within a crop. Yield changes from location to location according to the weather and the treatment of the crop during the cycle of growing.
- Environmental factors. The conditions of the weather have a strong effect on the rate of work. The weather could affect the soil and the crop conditions. Therefore the rate of work achieved by a machine is not a simple calculation of a single parameter but a complex one dependent on the above parameters and on operator skill.

McGechan (1982) suggested that it is important to know the overall or average rate of work rather than the spot rate of work. Delays arising from several causes account for differences between the two rates of work. He mentioned that some delays which occur at the beginning and the end of each operation possibly result from going to and coming back from the field or changing from field to field, or major breakdowns and should not be included in the field efficiency calculation. Daily servicing cannot be taken into account because they occur early in the morning before starting field operations.

The speed decision depends on the farmer's idea of how much time is required to finish the whole farm harvest area.

2.2.2 **Transport organisation**

Data were analysed by McGechan (1982) from four combine harvesters on different farms over three seasons in 57 machine days. The average time lost due to turning, unloading grain and other factors was 14.5%, 9.9% and 4.6%, respectively, of the working time. There was a clear relationship between field efficiency and the number of transport units used to load grain from the combine harvesters. Farms employed sufficient transport units to unload about 80% of grain on the move, giving an average field efficiency of 73.6%. Audsley and Boyce (1974) and Philips and O'Callaghan (1974) assumed values of 75% and 70%, respectively, in their operational research model of the cereal harvest.

Harvesting and transportation for one combine harvester can be organised in a number of ways.

1 - <u>One man harvesting operation</u>. The man can handle all the operations with one combine harvester and one tractor/trailer system. The combine harvester stops harvesting when the harvester tank is full, and is driven to a stationary trailer at one side of the field to unload the tank of grain. This sequence is repeated until the trailer is full. The man then leaves the combine harvester in the field and drives the tractor to the store and back to the field to repeat the same exercise until the end of the harvesting period.

2 - <u>Two man harvesting operation</u>. Two men can share the job of one combine harvester and one tractor/trailer unit. The

combine harvester can unload grain on the move, while cutting. It is a suitable system for a short distance between the field and the farm where the tractor man can drive to the store and back in less time than that required for the grain tank to be filled, otherwise the combine man must stop harvesting and wait for the trailer to return.

3 - Two man harvesting operation with one combine harvester, one tractor and two trailers. This system could be a combination of the first two. One trailer remains all the time in the field while the tractor takes the other trailer to the store. The combine harvester can unload the grain on the move when the tractor is present in the field. Otherwise, the combine harvester stops cutting when the grain tank is full, is driven to the empty trailer left at the field edge, unloads the grain and goes back to harvest.

4 - Three man harvesting operation with one combine harvester and at least two tractor/trailers unit. The combine harvester can unload the grain on the move without any difficulties, since the number of trailers present in the field is sufficient for the required combine harvester capacity. The combine harvester should not stop cutting to avoid an inefficient use of time.

The last system seems to be the more commonly used one but the number of trailers should be minimised depending on the demand of the combine harvester capacity.

2.2.3 Number of transport units

The number of transport units required for the transport of harvested material is equal to the ratio of the time used to complete an entire transport cycle of one unit to the loading time of the unit. The duration of the transport cycle comprises the time for loading, unloading, hitching, unhitching, transport and delays. Tischler (1959) calculated the number of wagons required for transport by establishing the following equation:

$$N_t = \frac{t_1 + t_2 + t_3 + t_4}{n_g(t_5 + t_6)} \qquad \dots 2.29$$

where
- N_t = number of transport units
- t_1 = loading time of trailer(s), h;
- t_2 = unloading time of trailer(s), h;
- t_3 = time for transport, h;
- t_4 = time for waiting, hitching and unhitching, h;
- t_5 = time of filling the grain tank, h;
- t_6 = time of unloading the grain tank into the trailer(s), h;
- n_g = ratio of wagon(s) volume to grain tank volume.

The denominator of the above equation is substituted by the ratio of the effective load capacity of one transport unit to the net combine harvester capacity in tonnes. The transport time (t_3) is twice the distance from the field to the store divided by the average speed used during the travel. By taking into account speed variation on slopes, road, field, with loaded trailers, and empty trailers the equation (2.29) becomes:

$$N_t = \frac{C}{L_t}\left(\frac{2d_s}{S_p} + t_w + t_L\right) \qquad \dots 2.30$$

where
- C = net capacity of the combine(s), t/h;
- L_t = effective load capacity of trailer(s), t;
- d_s = distance, km;
- S_p = speed, km/h;
- t_w = waiting time, h;
- t_L = time for loading, unloading and hitching, unhitching, h.

Many operations in the production and particularly harvesting operations of arable crops can be considered as close circuit cyclic transport systems (Boyce, 1971). Such organisation is made up of combined tractors and trailers which together move around a designed cycle of services. In cereal harvesting, for example, transport units may be tractors hauling matched trailers and combine harvesters. A transport unit must wait in a queue if a service is not ready to receive it or an unexpected delay occurs to the combine harvester. A number of operational research studies of cyclic transport systems have been reported (Boyce, 1973). The objective was to determine the optimum number of trailers in the unit system, either for maximum throughput or for minimum cost (McGechan, 1982). Dumont (1979) developed a mixed integer linear programming model to compare farm gross margins by using self propelled transport systems of combinations of tractor/trailer. His analyses are based on the best use of resources throughout the year.

Elrick (1982) quoted that the tank size should be considered in relation to the trailer size and the number needed for a system unit. The bigger the tank size, the more likely it is that a single trailer can cope. He suggested that it is worthwhile to have the trailer about one and a half times as big as the tank. The combine harvester is then left with maximum tank space and the trailer with minimum journey time. In a two-trailer system, Elrick (1982) illustrated his analysis by an example in which he concluded that the bigger trailer gains 30 minutes and the bigger tank gains only 6 minutes. Therefore, the choice of trailer size could be a wider range than the tank size.

For this study, the equation 2.30 was used to determine the integral number of trailers necessary to satisfy the combine harvesting equation. To avoid queuing theory which is a very complicated mathematical model, it is assumed that the capacity of the trailers utilised in the operation is the same and could be pulled by any of the selected tractors in the model. This constrains the field organisation which has been used in this study to a three man harvesting operation.

2.3 **Field workdays**

For efficient machinery management, a farmer needs information on the number of field workdays available in order to balance between timeliness costs of an inadequate system and the inflated capital costs of over-investment in machinery (Elliot et al. 1977). The time available to complete an operation depends on the length of suitable field workdays, number of workdays, percentage of usable workdays, machine reliability and field efficiency. The number of hours available each year ranges from few to a large number of workable hours. Incompleted operations at the proper time are penalised by high costs. The capacity of the machine system is determined by the number of hours that are available for each operation during the critical time periods. The most important times for most farmers or managers are sowing and harvesting. Those periods depend on the number of field workdays available between the start and the end of the time period in a year, and the number of hours a farmer is using per day for an operation. The number of suitable workdays fluctuates from year to year, so the selection of a number of workdays available for a particular location must be based on the average number of workdays that can be expected (Anderson, 1985). Environmental factors such as weather, soil type, date of start and completion of an operation determine the number of suitable workdays. The number of hours selected by a farmer reflects his evaluation of the size of machinery requirement from a management perspective.

2.3.1 Tillage workdays

The most widely used approach to obtain an estimate of days suitable for an operation is the conversion of weather data such as rainfall into the soil physical data, soil strength, plasticity and moisture content. A soil is workable if it has sufficient compressive strength to withstand the weight of the equipment, enough shear strength to meet the traction requirement with a tolerable percentage of wheel slip and soil damage. Working on too wet soil can result in serious damage to the soil by compaction and increase the costs due to excess travel reduction, extra time required for a task to be performed, and poor drawbar pull (Hassan and Broughton, 1975). They quoted also that a soil is assumed to be tractable if a tractor can perform an operation without land damage on a given soil type. Several researchers have used soil moisture balance models to predict soil tractability conditions (Shaw, 1965; Bolton et al., 1968; Rutledge and MacHardy, 1968; Frisby, 1970; Morey et al., 1971; Seliro and Brown, 1972; Holtman et al., 1973; Baier, 1973; Tulu et al. 1974; Elliot et al., 1977; Dyer and Baier, 1979; Rosenberg et al., 1982; Witney et al., 1982; Acharya et al., 1983; Babeir et al., 1986). Available field work time for an operation depends upon the calendar period specified for it, the portion of the calendar days available for a task and field work hours per day. Jose (1971) used an analytical criteria shown in Table 2.2. He classified the calendar days in three

Table 2.2 Classification criteria for field work activities on rainfall (Jose 1971)

Amount of rainfall (R) in 1 day	Same day	1st following day	2nd following day	3rd following day	4th following day
$R < .25$	2	2	2	2	2
$.25 \le R < .5$	0	1	2	2	2
$.5 \le R < 1.0$	0	0	1	2	2
$R \ge 1.0$	0	0	0	1	2

types: zero type day; one type day; and two type day which are defined respectively as: no field operation can be done; some operation can be done, and finally any operation can be done. The most uncontrollable and unpredictable variable which affect the completion dates of field operations are the number of available field days during different periods of the year. One way of looking at the problem is to estimate a prediction equation based on the rainfall data and temperature and apply it to a very long time series (Boisvert, 1976; Tulu et al., 1974). A probability distribution of suitable field days can be developed for each of several periods of the year. Suitable workdays calculated at 80% of probability can be interpreted as the workdays calculated or an average for all the seasons. Selirio and Brown (1972) used the 90% criteria for a loam soil to relate the estimated first dates of soil trafficability with the actual dates of field work at Guelph from 1946-1968. The approach of using estimates from the versatile soil moisture budget as a basis for determining the number of field workdays had been outlined by Baier, 1973.

Armstrong (1977) examined the effect of rainfall in September and October 1976-1977 on the water-table in drained and undrained plots and concluded that the surface layers of both plots rapidly become saturated and hence unworkable. A soil water balance model was developed to predict favourable tillage days for a farmer during the spring period (Witney et al., 1982). In their model, they predicted values of soil moisture in the top (300 mm) of soil profile from soil and weather information. Daily precipitation is balanced against run off and evapotranspiration. The model was developed to analyse and evaluate the workday's probabilities at different levels and soil workability criteria. Soil workability is directly related to soil moisture content. As the soil workability varies from soil to soil, from machine to machine and from location to location, it is impossible and unrealistic to adopt a value of moisture content of the soil to distinguish between soil workability and non-workability. A procedure has been used to enable the number of soil workdays to be calculated at different levels of soil moisture content or soil workability criteria. Various levels of field capacity were used as workability criteria to predict days available for field work using an optimisation model for tillage (Eradat Oskoui, 1981). In this method, the soil workability criterion for tillage work is chosen to maximise the tractor drawbar pull and to minimise the draught requirement to perform the task at a given moisture content. Eradat Oskoui (1988) suggests that a plastic limit is a fixed criterion in conjunction with a certain level of rainfall to identify a day being a workday or non-workday. The soil should not be worked at a moisture content exceeding the lower plastic limit.

2.3.2 Harvest workdays

Many methods have been adopted to determine the period of time available in which crop conditions are suitable for harvesting. Donaldson (1970) used a system based on "rain-free" days to determine the amount of available combine harvesting time and to produce cumulative grain moisture content curves for seasons with different numbers of rain-free days. Days on which not more than 0.25 mm were recorded as rain-free, but days when rainfall exceeded 0.25 mm were considered as rainy days. The duration of operations was restricted also by the grain moisture content. It was assumed that maximum operating time available on a combine harvester day is ten hours. Morey et al. (1971) suggested that a day was a working day when the moisture content of the soil in the top 152 mm (6 in) profile did not exceed 95% of the available capacity (amount of water held between field capacity and the wilting point) and when less than 2.5 mm of rainfall had fallen. Audsley and Boyce (1974) assumed that the combine harvesting operation would take place if the discounted sum of past rainfall was less than 1.27 mm. This discounted sum was the rainfall in the 24 hours plus 20% of the previous day's discounted sum. They assumed 9 hours per day of working day length at the beginning of the harvesting season (1st August), reducing by 0.02 hours per day thereafter. Grain was regarded as a total loss if the crop remained uncut 70 days after 1st August or if its moisture content rose above 30% (wb) towards the end of the season. Philips and O'Callaghan (1974) assumed 9 working hours per day. They set limits to the rainfall in the current and previous 2 hours, and the grain moisture content as calculated on an hourly basis using an algorithm derived by Crampin and Dalton (1971). The algorithm required hourly data on temperature, relative humidity and rainfall. Elrick (1974) recorded hours worked by combine harvesters in 55 farms over the East of Scotland during three consecutive years. Average hours per week available for combine harvesting decreased from 40 to 11 hours over a 7 week period. This wide range of hours is due to deteriorating weather conditions. From Elrick's survey data, two predictive equations of the available hours per week were developed by Bell (1977) as a function of rainfall measured in inches per week and mean daytime relative humidity or as a function of rainfall and the number of sunshine hours per week. The explained variation of the two equations is too low to be acceptable (around 70%).

Once an acceptable starting date has been reached, the time available for the completion of harvest is limited by the weather conditions during the operational period. Several days of high rainfall may stop the combine harvesting operation for a longer period than one day of heavy rain. The first determinate variable is a function of the number of hours worked in a day, the days which could be worked in a week, and the operation period for a specific task which is related to the crop to be handled. The total time required for a field machine operation depends on the capacity of the machine and the number of available working days. Each region or location of a country has a unique and specific climate, and different machine operations will have different criteria depending on the soil and the crop used. The time available for harvesting operations for grain and oilseed crops involves a compromise between the capital cost invested in the combine harvester capacity and the penalties in the form of crop losses associated with weathering of the crop when it is subject to adverse weather beyond the ideal harvest date (Anderson, 1985).

Glasbey and McGechan (1986) investigated criteria for deriving combine harvesting workdays from daily data. They proposed a criterion which stated that combine harvesting can take place when rainfall in the previous 24 hours is less than 1.4 mm. This value gave the best fit to their survey data.

2.3.3 Sequences of workdays

Many methods have been adopted to determine the period of time available in which crops conditions are suitable for farm operations. Many models have been proposed for simulating daily precipitation (Chin, 1977; Buishand, 1978). A first-order Markov chain (Bailey, 1964) was used to determine the occurrence of wet or dry days. With a first order Markov chain, the probability of rain on any day depends on the wet or dry status of the previous day. This method was also used by Caskey (1963); Weiss (1964); Hopkins and Robillard (1964); and Wiser (1966) to determine the occurrence of sequences of wet or day days. Maunder et al. (1971) judged that a Markov chain probability model was suitable for road construction workdays. Similar results were found by Hayhoe and Baier (1974) for field workdays. Kedem (1976) generated the mathematical distribution of workdays for any period by presenting an efficient algorithm for which the Markov chain coefficients were determined. Hayhoe (1980) confirmed the suitability of the second order Markov chain model. The result of his analysis is a matrix of binary data with 1 as workday and 0 non-workday. Also, the Markov chain model has been used to provide a suitable probability model for sequences of wet and dry days (Gates and Tong, 1976). Richardson (1981) used a first Markov chain with only two states, namely wet or dry. A day with a total rainfall of 0.2 mm or more was considered a wet day. The same procedure was adopted by Coe and Stern (1982). They quoted that, in a Markov chain, the probability of rain falling on any day depends on the state of the previous day as wet or dry. The probability of rain on day t is conditional on day t-1 being in a state i in which i could be 1 or 0, respectively dry or wet. Stern and Coe (1982) used in the first part of the model, results from an analysis of the chance of rain through the year. A rainy day was defined to be a day with 0.1 mm of rain or more. It is necessary to consider the four possibilities for the two previous days, depending on whether they were two dry days or two wet days, or one wet day followed by a dry day or one dry day followed by one wet day. There are three methods of obtaining results from the model. The first is analytic, the second is to use the Markov properties to derive recurrence relations for the results of interest. This method is described by Stern (1980; 1982) and used a numerical procedure, effectively solving a set of equations repeatedly, one set for each day. The third method of deriving results is to use the method to simulate rainfall data and then analyse the simulated data. Long records may be simulated so that the results are relatively smooth. Generation of a sequence of wet and dry days from the Markov chain is straightforward.

A detailed study by Dennett et al. (1983) indicated that there was no dependence between rainfall at different times within the rainy season at three sites in West Africa, confirming other work from India.

For this study, a simulation model of generating sequences of dry and wet day was built using Markov procedure. Since there is no dependence between periods of time, this justifies the procedure of breaking the year down into different periods and estimating the number of available workdays within periods and formulating constraints. Markov processes using the previous day's influence appear to be adequate for all practical purposes in generating sequences consistent with the observed data. In each period the number of available workdays over the last 24 years are ordered from the maximum to minimum. Cut off points corresponding to any level of probability chosen to work with can be made. This approach is very simple and direct. Such an approach does not adequately cope with sequential operations depending on different criteria. A simulation model is achieved to generate and determine the conditionally available workdays consistent with any given probability level based on a chosen criteria.

2.4 Crop losses

Farmers have the opportunity to spread crop planting over a period of time described by the starting date and the finishing date, and thus reduce the need for expensive, high capacity machines. Good management may include planting different crop varieties in rotation to obtain this range of starting dates. For field operations which have two or more distinct optimum times, the timeliness costs equation must be divided by the number of the optimum dates (Gao and Hunt, 1985). The duration of field operations can be calculated as:

$$t_f - t_s = A/(h_d M_a W_r W_d) \qquad \dots\ 2.33$$

where
t_s, t_f = starting and finishing dates of an operation;
A = area, ha;
h_d = working hours per day, h/day;
M_a = availability of the machine, decimal; (1 - decimal of down time)
W_r = working rate of the machine, ha/h;
W_d = proportion of working days to calendar days.

The timeliness cost results from the loss in income from the crop because a farm machine was not operating properly or not operating at the right time. Reduction in both yield and crop quality are included in timeliness cost (Hunt, 1981).

Farm operations are sequential in nature. There are optimal dates of sowing and harvesting appropriate to each crop and specific to individual varieties and locations. Deviations from these optima result in crop losses. Investment in machine capacity may reduce these losses.

2.4.1 Optimum sowing date

The optimum date on which an operation should be performed is the day when the crop yield reaches a maximum value. It is necessary to start early at a date before the optimum date and finish at a date after the optimum date. The longer the interval, the greater the losses of the crop yield.

Link (1967) assumed that the crop yield varied in some predictable way as a function of the time of operation (Fig 2.2). Each field operation is expected to have a distinctive optimum day and timeliness cost associated with it. The optimum operational day may be defined as that day of the year when the maximum potential returns are obtained from the crop.

Results from trials of spring wheat at various Experimental Husbandry Farms were reported by Francis (1974). Four varieties were sown at three dates in each of three consecutive years. Francis confirmed that there is no relationship between sowing dates and varieties. Results obtained from potatoes (King Edward variety) planted on three dates over three years (Baldwin, 1964; Palmer and Jarvis, 1977) varied considerably depending on time of planting from

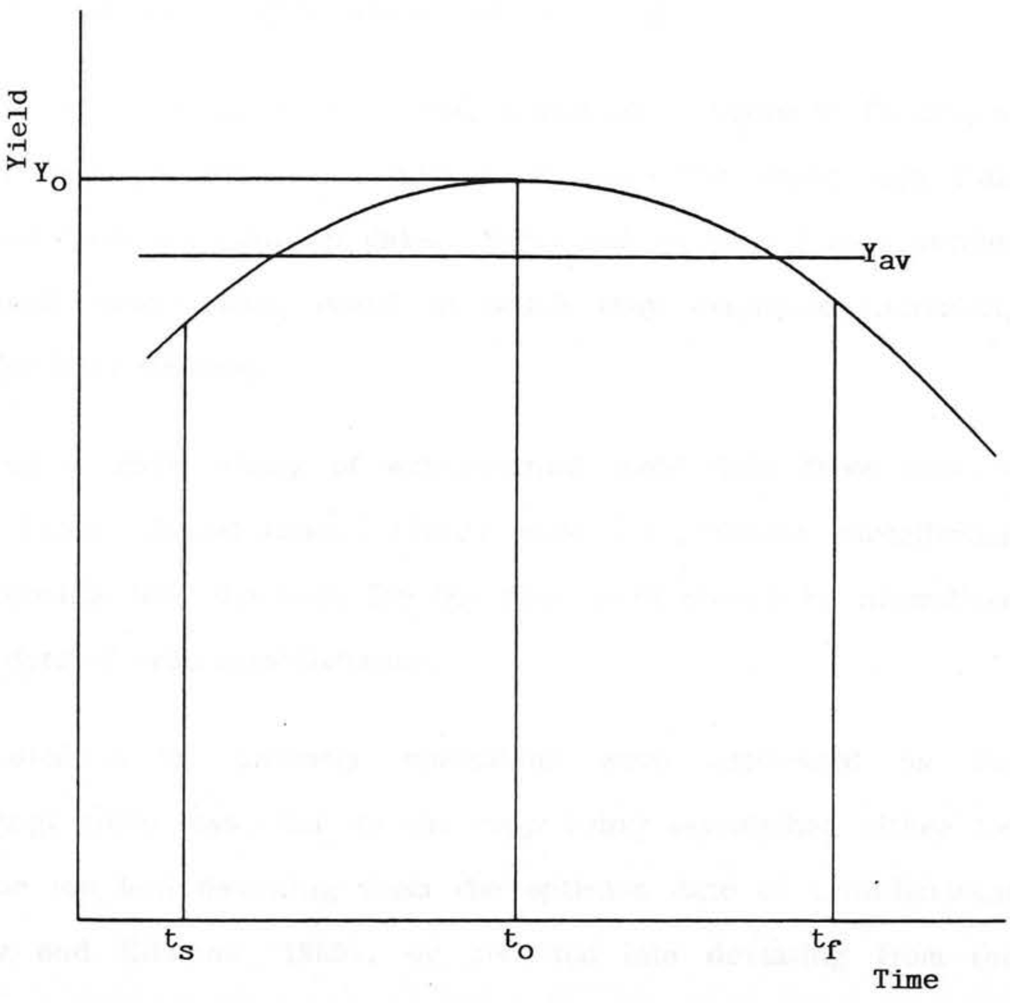

Fig 2.2 General form of the yield response curve, showing the peak yield, and the average yield for a timespan (Witney and Elbanna, 1985)

year to year. Yield fell appreciably when planting was delayed beyond the third week of the trial. Jarvis (1977) concluded that only for winter wheat is there evidence that the effect of time of sowing varies with variety, but it does not with spring wheat and barley. The effect of sowing date is compounded by the effect of weather condition before sowing, as far as it affects seed quality, soil moisture content, temperature at the time of sowing and weather condition, and day length subsequent to sowing.

Edwards and Boehlje (1980) used continuous quadratic functions, derived from experimental results to estimate the percentage yield reduction from the planting date. Scott and Audsley (1981) applied a dynamic programming model in which they evaluated increasing costs for later drilling.

Following a major study of experimental yield data from date of sowing trials, Eradat Oskoui (1983) made a significant contribution by proposing that the base for the crop yield should be normalised to the date of crop establishment.

The penalties of untimely operations were expressed as the percentage yield loss, due to the crop being established either too early or too late deviating from the optimum date of establishment (Witney and Elbanna, 1985), or just too late deviating from the starting date of ripeness for harvesting. From the experimental yield data for eight arable crops, the following equation was based on a square function of the deviated time from the optimum starting point:

$$Y_L = k_t \, (t_o - t_a)^2 \qquad \ldots \; 2.34$$

where Y_L = percentage yield loss;
k_t = timeliness coefficient;
t_o = optimum date, day;
t_a = actual date, day.

Different timeliness coefficients for early and late establishment allow for assymetry of response curves (Fig 2.3). There is a number of problems in reporting the results of experiments where the dates of sowing have been varied depending on each year. Chen and McClendon (1984) developed a soybean planting and harvesting simulation model to determine an optimal time to plant soybean in the mid-south of the United States. Delays in planting and harvesting were included by using excessive rainfall to postpone field operations. Twenty years of historical rainfall data records were used in their model to find a planting date which gave maximum economic return under selected machines.

2.4.2 **Optimum harvesting date**

For the full potential seed yield to be obtained, cereal crops must have reached at least morphological ripeness before harvesting commences (Geslin and Jonard, 1948). Another variable requiring a decision from a farmer or a manager is the date at which harvesting should begin. The NAAS survey in 1969 showed that there was some agreement over the point of starting harvest because a minority of farmers started cutting their crops at over 20% grain moisture content while the majority waited until the moisture drops below 18% m.c.

Hull and Webb (1970) investigated the effects of time of lifting the sugar beet crop and the sowing time. They stated that there was no interaction between the two times and the effect of harvest date on

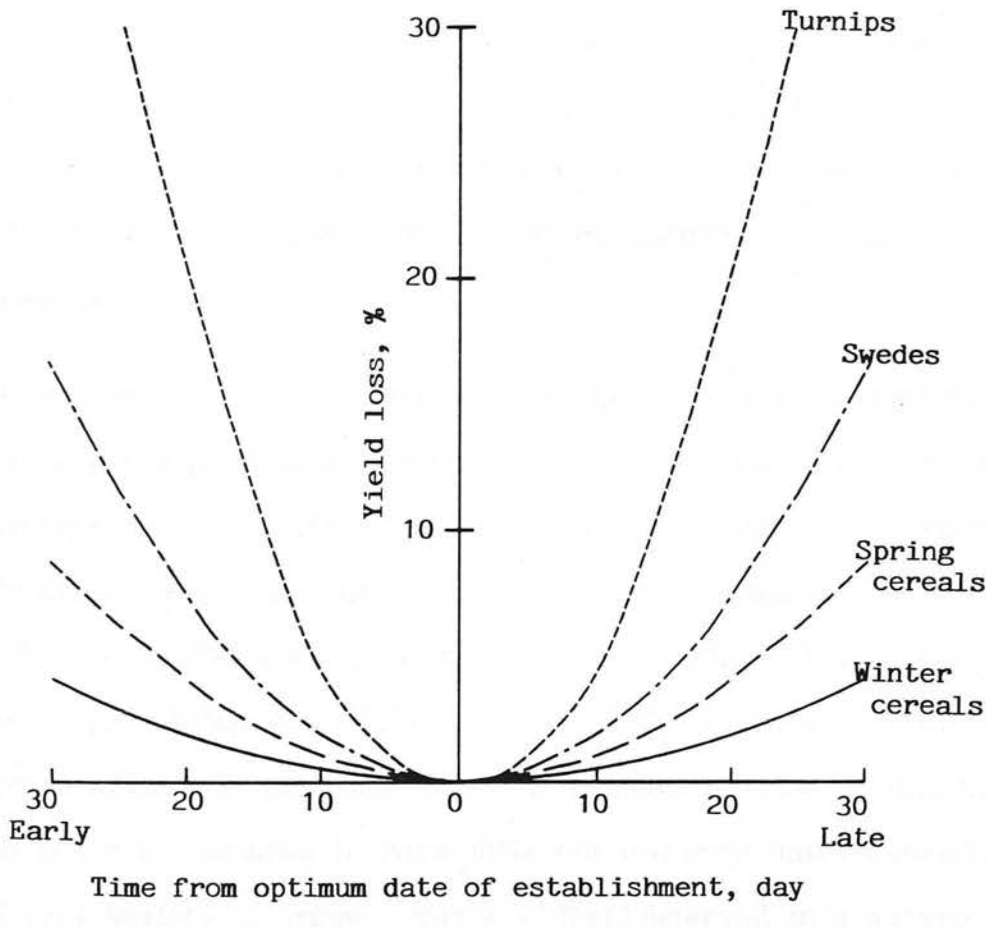

Fig 2.3 Percentage yield losses from untimely crop establishment (Witney, 1987)

sugar beet fitted in a quadratic regression line to show a steady increase in yield up to the end of October but little change after early November. The time of lifting early potatoes is considerably affected by both economic and agronomic factors (Jarvis, 1977). The length of the period in which the product of yield is at the maximum level may vary for many reasons outside the farm's control. The farmer requires to collect the largest amount of yield in the shortest time.

Patzold and Dambroth (1970) stated that there is evidence that potatoes become more susceptible to mechanical damage as soil temperature falls and moisture content increases. Jarvis (1977) concluded that earlier harvesting would be entirely advantageous in most seasons.

Sowing spring barley as early as possible ensures a significant increase in grain yield due to early establishment and early maturity. This creates more flexibility for harvesting operations and reduces possible crop damage through late harvesting or no harvesting at all. In all the early simulation models reviewed by Elrick (1974) and in the Philips and O'Callaghan (1974) model, all the grain on a farm was assumed to mature on the same date. A number of crops in one farm rotation could be assumed to have different maturity dates depending on different variety of crops. Elrick (1974) observed in a survey on a large number of farms in Scotland that, even when spring barley was the only crop grown, there was a spread of maturity dates of up to 10 days depending on the variety, sowing dates and the previous crops; with winter barley an even wider spread could be possible.

Elrick (1974) pointed out that by careful selection of crops, varieties and other factors, farmers may be able to reduce standing time of mature crops. Using ten years weather record data from several locations, Audsley and Boyce (1974) determined whether harvesting could take place each day from consideration of the rainfall on the current and previous days. They used a sixth order polynominal equation to calculate the starting time at 30% of moisture content fitted to data for spring barley recorded at four sites in England (Everett et al. 1972). McGechan and Glasbey (1982) stated by way of criticism that harvesting could start at 19% moisture content some 15 days after the 30% moisture content used in the Audsley and Boyce moisture content curve. Glasbey and McGechan (1986) assumed that combining could start with a moisture content of 21% (w.b) on 20th August, as an average date observed in the survey.

2.4.3 **Harvesting losses**

There are two main sources of grain loss during the cereal harvest (fig 2.4), those influenced by harvest duration between maturity and harvest (front end loss)

- dry matter loss
- shedding loss
- cutter bar loss

and that influenced by crop flow rate through the harvester: threshing losses. Dry matter and shedding losses are generally considered together because both occur naturally before harvesting takes place. Cutter bar loss is initiated by the passage of the combine harvester through the crop. All front end losses increase with the time that the mature crop stands in the field before being cut. Audsley and Boyce (1974) used second order polynominal equations to present shedding loss and cutter bar loss. There are,

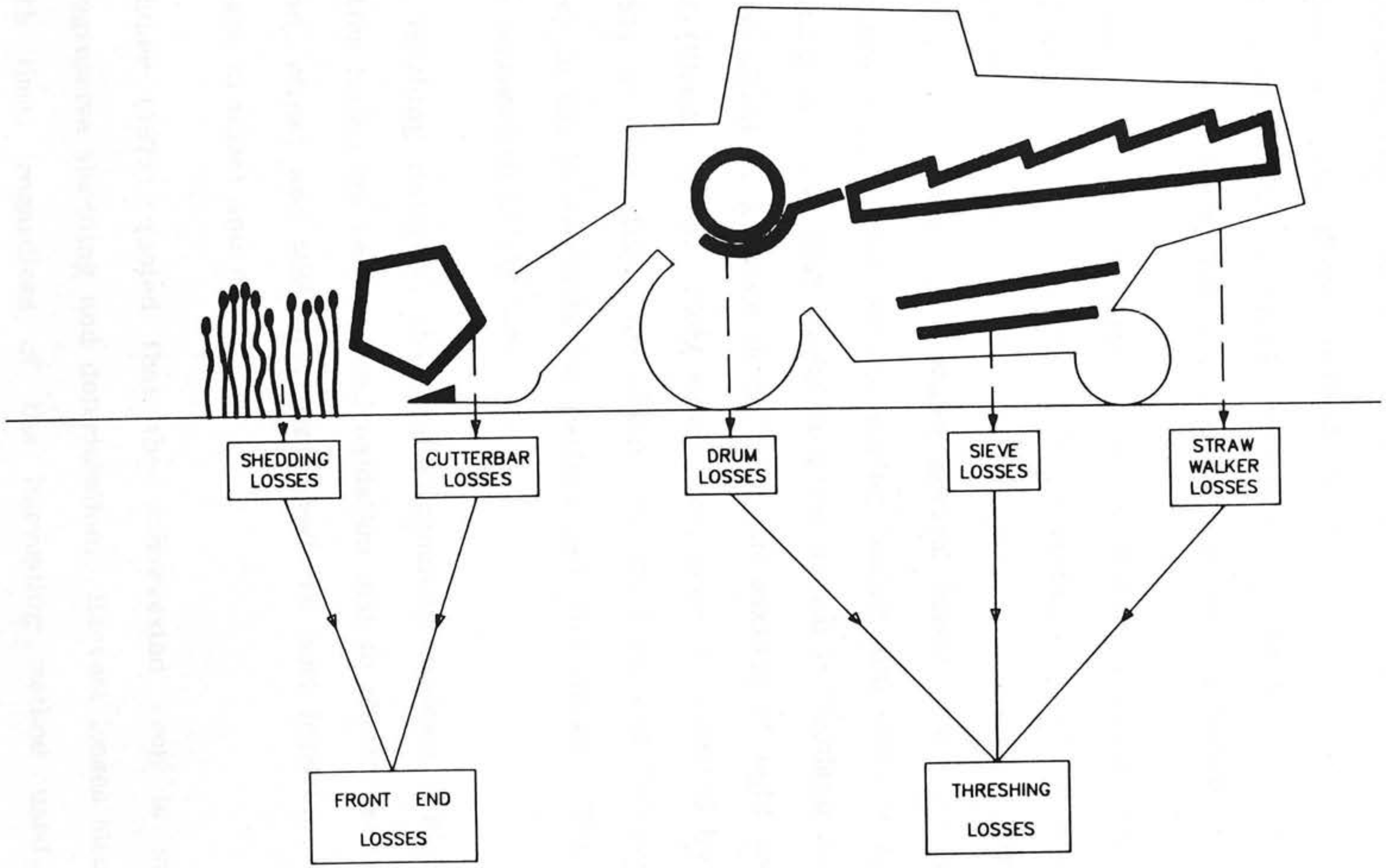

Fig 2.4 Harvesting losses

however, significant differences in these losses for different crops and even for different varieties of the same crop. Barley straw, being more brittle than wheat straw, exhibits the greater proportion of shedding loss. The cutter bar loss occurs mainly to heads being broken off and grain worked to the ground during combine harvesting. Thus shedding accounts for the predominant loss in wheat, whilst cutter bar loss is more important in barley.

For the assessment of harvest duration losses, a single ripening date is often adopted for the whole area whereas, in practice, a spread of ripening of less than seven days is unusual for a single cereal crop, such as spring barley. Where several cereal crops are grown in rotation, e.g. winter wheat, spring barley and oats, a spread of ripening of up to four weeks is quite normal in Scotland due to the added effect of a range in altitude and mixture of light and heavy land (Elrick, 1974). Field losses have been investigated by Johnson (1959) in Ohio, USA, for wheat, by De Jong and Zelhorst (1967; 1968) in the Netherlands for barley, oats and wheat. Their results are summarised in Fig 2.5.

On reaching maturity, the crop immediately becomes subject to dry matter losses by leaching and oxidation and to shatter losses due to wind, birds, and wild life, considered the most important source of losses in wheat and oats.

Klinner (1979) quoted that the unharvested crop is subject to progressive shedding and deterioration. Harvest losses also increase with time, regardless of the harvesting method used. It is economically sound to plan and aim for minimal delay after crop maturity is reached. The accurate assessment and interaction of the

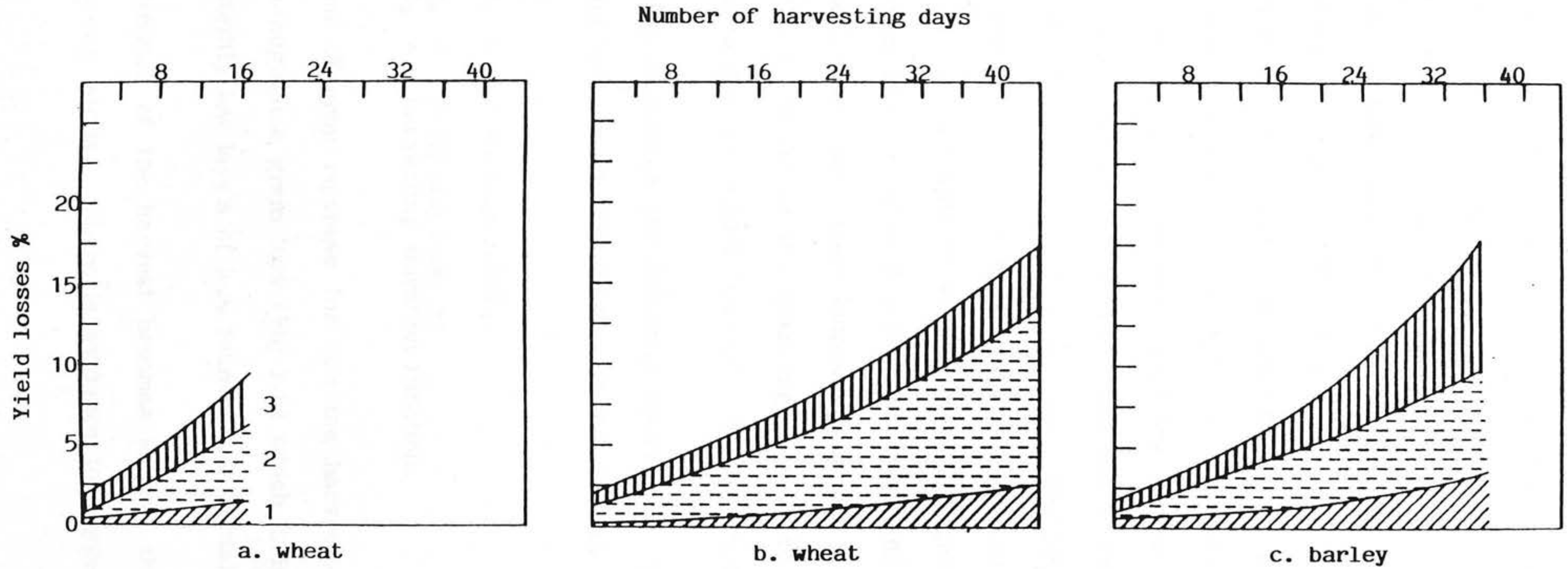

Fig 2.5 Sources of field losses of wheat and barley as the harvest date progresses:
1- dry matter loss; 2- shatter loss; 3- combine header loss.
(a) after Johnson (1959); (b,c) after De John and Zelhorst (1967).

individual sources of grain loss influence the optimum size of a combine harvester and the alternative speed strategies for various crops and conditions on a particular farm. Adjusting the forward speed on the combine harvester to maintain a constant throughput of material other than grain will reduce the total grain loss in the harvest, compared with that when operating at constant speed. The extent of this loss reduction depends on the convexity of the loss throughput relationship and the variability of the yield of material other than grain throughout the field (McGechan and Glasbey, 1982). The area covered per hour for a particular machine is a function of operating speed, cutter bar width and field efficiency. For a given operating speed and length of working day, it is possible to calculate the time consumed to cover a particular area, and then the cutter bar loss which will have been increasing as the crop becomes more mature. Thus the slower the operating speed, the greater the area to be covered and the higher the cutter bar loss/hectare.

Elrick (1982) suggested the following equation to represent the sum of shedding and cutter bar losses, based on Van Kampen's curves for barley.

$$y_s = 0.022 \exp(0.05X_2) \qquad \ldots 2.35$$

where y_s = front end loss, %;
X_2 = harvesting duration function.

At the time of crop ripeness for combine harvesting, the equation predicts a negligible grain loss (Fig 2.6) which is in agreement with the consistently low levels of loss found experimentally.

As the duration of the harvest becomes longer, there is a greater risk of strong winds. There is evidence to suggest that crops at

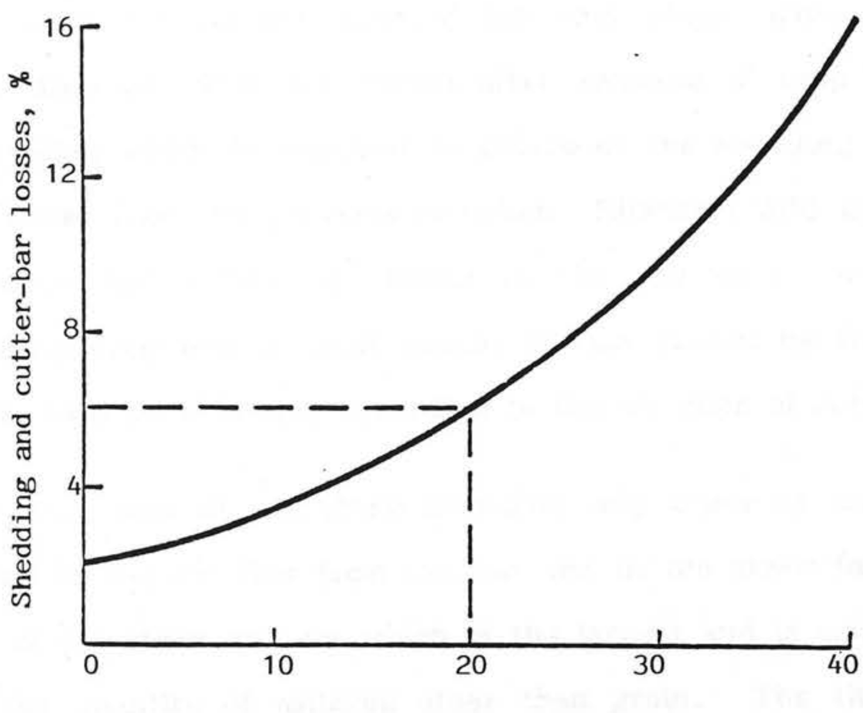

Fig 2.6 The effect of harvest duration on shedding and cutter-bar losses, as a percentage of the original yield at the time of crop ripeness for combine harvesting (after Elrick, 1982)

the unripe stage are immune from gale damage. Even when the crop just reaches the stage of ripeness for combine harvesting, only a moderate loss of approximately seven per cent is sustained from gales. The percentage of total yield lost is influenced by the proportion of the crop at risk as the harvest proceeds, depending on the spread of ripeness and the daily rate of harvesting. If harvesting proceeds at a uniform rate over a harvest period, i.e. 15 days, then one-fifteenth of the crop area is harvested daily. Suppose that harvest starts on the day when the first part of the crop reaches ripeness for combining, consecutive parts of the crop are at risk for the timespan (x_h - x_r) in Fig 2.7, where x_h is the date of harvesting that part of the crop which ripens on day x_r. This timespan gives the period after ripeness of crop for combine harvesting which is required to determine the shedding and cutting bar losses from the previous equation. Klinner (1979) has presented evidence that cutter bar losses in the laid crop, or even in a standing crop with a small amount of lean caused by the prevailing wind, vary considerably according to the direction of cutting.

Threshing loss in a combine harvester may occur at the drum, the sieves in the air flow from the fan and in the straw falling off the end of the straw walkers which is the largest and is most influenced by the quantity of material other than grain. The threshing loss rises with throughput of the combine harvester. Many characteristics of the crop influence combine harvester threshing loss, such as moisture content of grain, dampness of straw, but it is assumed generally that the most important factor is yield of material other than grain. Boyce and Rutherford (1972) and Audsley and Boyce (1974) assumed a relationship between threshing loss as a

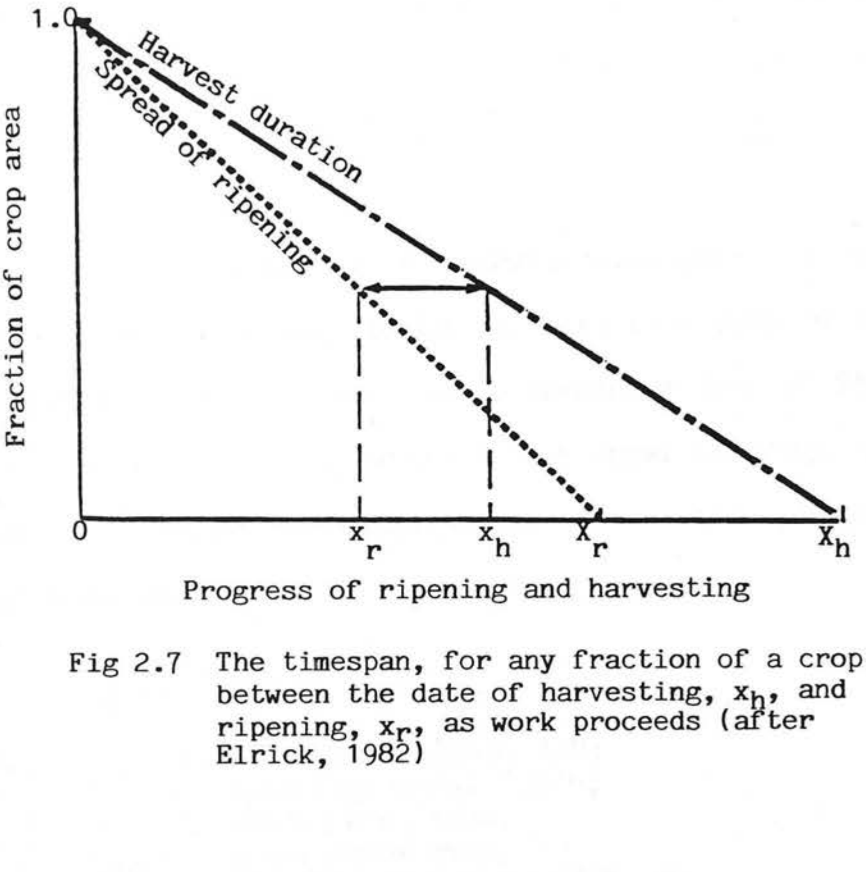

Fig 2.7 The timespan, for any fraction of a crop, between the date of harvesting, x_h, and ripening, x_r, as work proceeds (after Elrick, 1982)

proportion of available yield and throughput of material other than grain. Philips and O'Callaghan (1974) fitted an exponential curve to their data for threshing losses against throughput of material other than grain. McGechan and Glasbey (1983) found the analysis of constant threshing loss operation was not a useful exercise. After a critical reappraisal of the work of Audsley and Boyce, and of Philips and O'Callaghan, they concluded that the loss equations which seemed closest to the experimental data are the Audsley and Boyce front end loss equations and the exponential threshing loss equations given by Philips and O'Callaghan.

The rated throughput of a combine harvester, as quoted by a manufacturer, is usually based on tests in a crop of wheat with a grain/straw ratio of unity and a threshing loss of 2%. In many cases, the ratio of grain/straw is not equal to unity, so it is more accurate to relate threshing losses to the throughput of material other than grain which is given by the equation:

$$A_h = 0.1\, S_p\, W_e\, Y/R_{gs} \qquad \ldots 2.36$$

where A_h = actual throughput, t/h;
S_p = operating speed, km/h;
Y = grain yield, t/ha;
R_{gs} = grain straw ratio;
W_e = effective operation width, m.

Thus the threshing loss curve against throughput is related to the ratio of the actual throughput, and the rated throughput:

$$T_L = 2\left[\frac{A_h}{A_r}\right]^2 \qquad \ldots 2.37$$

where T_L = threshing loss, %;
A_h = actual throughput, t/h;
A_r = rated throughput, t/h.

McGechan (1985) demonstrated by sensitivity analysis that the level of threshing loss had the greatest influence on combine harvester forward speed, and variability from year to year, crop to crop; front end loss appeared to have a relatively small effect on optimum speed.

For this study, the date of sowing and the date for harvesting can be logged for each crop of the chosen rotation. Optimal dates of sowing and harvesting are appropriate to each crop specific to individual varieties and locations. Deviation from these optima result in crop losses. The model in this study for selection of machinery takes into account both cost and timeliness penalties due to duration from the optima. Witney and Elbanna (1985) have drawn data on crop losses for the major arable rotation crops in the UK which facilitate the application of timeliness penalties' calculations in this study.

2.5 Models for scheduling

There are many ways in which scheduling problems can be classified, such as static or dynamic, deterministic or stochastic, single period or multi-period, single machine or set of machines. Scheduling problems and the methods employed for their solution are defined by their objective and constraints, the relationships between them giving rise to numerous perturbations (Eilon, 1979). The analysis of scheduling problems involves a range of approaches:

- linear programming,
- dynamic programming,
- simulation programming,
- queuing theory,
- use of operational games,
- network analysis,
- heuristic strategy.

It is proposed that there are four main dimensions with which farm scheduling problems can be adequately described:

- a formation of activities framework,
- specification of objectives,
- system of constraints,
- determination of decision variables.

2.5.1 **Linear programming**

Nilsson (1973) developed an analytical procedure which produced an optimal value of the objective function with integer variable values. The farmer has to make the decision on the mechanised system; its capacity and its purpose. The aim of the method is to determine the objective function for the lowest cost solution and to use that function to identify the optimal solution. At a later date, he used a linear programming model to select equipment and a cropping plan (Nilsson, 1976).

Candler et al. (1973) compared the simulation results reported by Thompson (1970) with the optimum solution obtained using a mixed integer programming algorithm. They presented an example of a problem that was analysed initially by simulation and has subsequently been solved by means of a linear programming. It was argued that simulation algorithms are not necessarily preferable to analytic procedures.

McCarl et al. (1977) presented a linear programming model for farm planning known as "The Purdue Top Farm Cropping Model B". The model is designed for direct use with farmers and has been used successfully by more than 5000 individuals. Anderson et al. (1977) reported that linear programming is a popular tool for the analysis of a whole farm cropping system. Elderen (1980) mentioned that linear programming is a technique used often to find an optimum cropping plan for one year. It is also used to select machinery simultaneously with the crop plan. Combinations and sets of gangs as decision variables are sufficient to guarantee an executable schedule but are not yet used (Schmidt, 1971; Tseng and Mears, 1975; Nilsson, 1976). The structure given by Elderen in 1977 demonstrated much more details of scheduling than is generally found in the model. He recognised that the best way forward so far was given by Nilsson (1976).

Brink and McCarl (1979) reported that plans generated by linear programming models are assumed to be repeatable year after year, with the spring and autumn operations in one year being determined simultaneously in the model. In reality, spring operations are influenced by the autumn operations that were or were not done in the previous year, and autumn operations of the current year influence the spring operations of the following year. They analysed how much the usefulness of a linear programming crop planning model is affected by the continuity of cropping activities between years, but the model covers only one year. Brink and McCarl (1978, 1979) also studied risk modelling and have outlined procedures whereby risk aversion can be incorporated into the model. The model was run for a 300 ha farm using Indiana weather data and soil type (Parsons and Doster, 1980). Typical machinery sets and working rates were used in the case study (Doster and McCarl, 1981). Danok et al. (1980) concluded that machinery selection could be modelled by four alternative approaches such as mixed integer programming with an individual machine or with sets of machines, by using a stochastic dominance method, or simply by deterministic models that can be used to examine the impact of alternatives. The models maximised the profit subject to constraints:

- on resources which link machinery and crop activities,
- that reflect initial exclusivity of machinery,
- which link machine set purchase and use,
- on other cropping resources.

Krutz et al. (1980) used a linear programming model to evaluate alternative farming situations in order to provide general guidelines of machinery selection for maize and soybean production. Their report indicated that linear programming models can be extremely useful tools to individual farm managers for evaluating machinery sizing decisions for a particular situation. Fokkens and Pulyaert (1981) presented a linear programming model in a length of six intervals of variables. The model predicted a realistic schedule of operations for harvesting grain.

Whitson et al. (1981) utilised a linear programming approach for the selection of machinery complements and cropping patterns in Texas under weather risk. The objective was to maximise profits. They used probability of completing field work on time to evaluate crop alternatives. McCarl and Nuthall (1982) reported that linear programming can be applied to a variety of problems in agriculture such as research work (Danok et al. 1978), advisory work (McCarl et al. 1978) and teaching policy (Scherbing and Zaki, 1974). They also mentioned that the model could be useful for prescription, prediction and description. Several other computer models have been used for machinery selection. Whole farm, profit maximising, linear programs have been used in applied research, advisory and farm machinery workshops (Doster, 1981; Black and Harsch, 1976).

Linear programming for machinery has limitations as a solution algorithm since it tends to indicate fractional numbers of machines. Either mixed integer programming must be used or a conditional optimisation approach where the user provides input for a specific complement, deduces the sequences and provides input for a revised complement in an interactive procedure until a suitable complement is determined (Rotz et al. 1983).

Several expert systems have developed recently for agricultural systems. Fisher et al. (1984) presented a rule-based expert system for selecting forest harvest equipment. Michalski et al. (1983) designed an expert system to diagnose soybean diseases.

Bender et al. (1984a) concluded that the major limitation of the model in linear programming is that solutions are based on a long run steady behaviour. So the model does not consider variations in between year linkages such as field operations which may carry over from the autumn to the spring. Bender et al. (1985) quoted that linear programming generates extensive outputs on machinery schedules, shadow prices for each scarce resource and crop yield. Linear programming experts are usually needed to interpret the model outputs for the farm managers due to the complexity of the output and to aid in iterative analysis of alternate machinery sets. The model has been the most popular line attack in machinery selection due to its analytical power and relatively few restrictive assumptions (Bender et al. 1985). Shadow prices are often used to identify binding resource constraints in these models. A shadow price reflects the contribution to the objective function per unit increment in the right hand side of the matrix as long as the linear programming basis does not change. Problems arise when the acquisition of a machinery resource changes the coefficient within a number of contraints (McCarl and Nuthall, 1982). Schueller et al. (1986) developed an expert system with speed syntheses for troubleshooting grain combine harvester performance. Kline et al. (1986) presented an intelligent decision support system for machinery sizing and selection in farm level cropping systems which represented an extension of Bender's (1985) expert system.

Freesmeyer and Hunt (1985) used a machinery optimisation program algorithm which incorporates chance-constrained programming to allow the operator to introduce statistical probability in choosing an optimum sized set of machinery for his particular farm. Bender et al. (1984b) tried to find an optimum probability level of the good field days in a chance-constrained linear programming model. The essence of chance-contrained programming was used by Charnes and Cooper (1959).

A mixed integer linear programming model has been developed by Ghassan Al Sobah et al. (1986) to select the optimum harvesting method and machinery system. The results of the model indicated that the upright navybean variety, planted in 70 cm row spacing and harvested directly, was more profitable than any other alternative to a navybean production system. In mixed cropping systems, sugar beet was the most profitable crop. Hanley and Lingard (1987) used a linear programming model to estimate the costs to farms of policies imposed on them to ban or reduce the level of straw-burning using data from Murphy (1985), Audsley (1984b), Nix (1984) and Sanders

(1984). They concluded that linear programming is a useful method for estimating the relative costs of a range of policies available to control the generation of externalities.

Elderen (1988) described linear programming as an image of the real scheduling problem under the given assumptions. He concluded that linear programming is restricted for every interval to one workability level; although the workability level between intervals may vary, the model does not handle several levels per interval. Very often, decision variables in linear programming could be the areas of crop and they are only restricted by constraints on the number of hours of men, tractors, machines or workable time (Audsley, 1981). The operations are only represented as coefficients (rate of work) and simultaneous use of men, tractors and machines within an operation is not considered. Elderen (1988) quoted that the main emphasis for practical models should be on linear programming and simulation models. A simulation model is not particularly efficient, however, for selecting machinery. He assumed that it is worth using a general linear programming model to select machinery and then using a simulation model to check the performance of the machinery.

2.5.2 **Dynamic programming**

Dynamic programming was introduced by Link (1962) and Link and Bockhop (1964). They used a sequence of jobs on a maize growing farm with the weather affecting operations. Hunt (1963, 1969) extended the mathematical treatment of the machinery selection problem to include dynamic variables. Holtman et al. (1970); Carpenter and Brooker (1970) developed models of maize harvesting systems. They included the interactions of field harvesting rate, weather, drying and some marketing alternatives.

A dynamic model with weekly intervals to harvest maize is given by Morey et al. (1971), and further extended in 1972. The model can aid the decision maker in scheduling the important feedback property which makes dynamic programming a useful and practical tool (Morey et al. 1972). Sowell and Link (1971) applied dynamic programming models to machinery replacement problems for cotton picking. Corrie and Boyce (1972) also applied a dynamic programming procedure to the cauliflower harvest which is sensitive to timeliness of operation. Swain and Ojha (1980) developed a computer algorithm based on a network analysis and dynamic programming models to find out the combination of methods to give optimum and near optimum costs of production.

Audsley (1984a) described a model to select machinery for ploughing and drilling in the autumn. In his model, the daily decisions are reached on the basis of weather uncertainty, soil moisture and timeliness of operations.

Elderen (1988), by comparing different programming models, described dynamic programming as an interval presented by each day of a season, the beginning of an interval being a stage in the dynamic model of the scheduling problem. The state of the system at each stage includes the areas of crop and the workability on that day. A solution can be derived for each specific season by using the strategy. A model with weekly intervals to harvest maize is given by Morey et al. (1971).

Dynamic programming is a method for solving optimisation problems which can be formulated as a sequence of decisions. Unlike most other mathematical programming techniques, it is not a variant of linear programming. The term state is defined as the configuration of a system and stage as a transition from one state to an adjacent state in dynamic programming.

2.5.3 **Simulation**

A simulation model can be described in the same manner as dynamic modelling with stages, states and decisions. The simulation model differs from dynamic programming in its solution procedure. The dynamic models work both ways, forwards or backwards, to achieve an optimum solution. The simulation works only one way, forwards, and a strategy has to be implemented in the model (Elderen, 1988). Van Kampen (1969) had considered various crops such as oilseed rape, barley, oats and winter wheat in his simulation experiment on harvests on the Dutchpolders. He applied simulation to determine the optimal grain harvesting system by minimising the sum of the costs of labour, equipment and product loss due to any selected system. A simple strategy was applied that starts and stops harvesting with the combine harvester (Van Kampen, 1971; Dalton, 1971; Philips and O'Callaghan, 1974). Hughes and Holtman (1976) utilised a simulation model to evaluate alternative machinery systems which would meet predetermined machinery requirements. Alternative tractor sizes and associated equipment were evaluated in order to select a machinery system that was "best" in terms of capital, energy consumption, labour and annual operating costs. The time constraints algorithm has been further developed by Singh (1978) and Wolak (1981). The approach has worked well in determining the best size for a machinery complement given the date constraints, suitable days available and operation requirements.

Thesen (1976) presented an heuristic scheduling of activities under resource and precedence restrictions which is a relatively common problem that has received less consideration. The algorithm differs from others in two major respects. First, an optimising resource allocation is employed to select activities to start at different points in time. Second, a new hybrid heuristic urgency factor is introduced to capitalise on the optimising capabilities of the selection procedure. Elderen (1977) developed a simulation model with an heuristic strategy for scheduling combine harvesting, straw baling and loading, and ploughing. Singh and Holtman (1979) developed a heuristic algorithm to evaluate and compare selected crop production systems over a range of farm sizes with respect to costs and requirement for machinery, labour and fuels for field work. Singh et al. (1979) used the same model to analyse 29 cash crop production systems of southern Michigan. They utilised in their analysis ten crop rotations and three tillage systems. They concluded that the crop rotation system can increase machinery utilisation and decrease its requirements and the cost per hectare. Models have been developed which select machinery based on time constraints of various operations on the farm. Some more approaches included simulation models (Charlton and Thompson, 1970; Anderson, 1974; Barrett and Peart, 1982). Edwards and Boehlje (1980) used a model to simulate the completion of field operations and determine net after tax machinery costs. They used a yield reduction function coupled with suitable field day data for Iowa to find the least cost equipment set. McClendon et al. (1981) used a simulation procedure in their cotton harvesting model which begins by labelling each day as an acceptable or unacceptable field day. Rotz et al. (1983) developed a machinery selection algorithm to determine the preferred machinery complements for a variety of crop rotations in Michigan. They used a time constraints approach which considered suitable field days available and the power requirements for each operation. They also included a cost analysis to determine a machinery complement for maximum profit for different crop rotations. They used probability levels to determine days per week which are suitable for field work.

Witney and Eradat Oskoui (1982) incorporated a soil moisture simulation model in their study to show the feasibility of a comprehensive computer program for the selection of tractor-plough combinations for a given climate and soil type within a machinery, labour and timeliness penalty cost framework. Further advances with this approach were reported by Elbanna (1986).

Chen and McClendon (1984) developed a soybean planting and harvesting simulation model to determine an optimum time to plant soybeans in the mid-south of the United States. They extended this analysis to simulate a soybean and winter wheat double cropping system (Chen and McClendon, 1985). McClendon et al. (1987) used the model to simulate field preparation, planting and harvesting on a daily basis with resulting yield for both crops. The economic returns per year were analysed to determine a preferred equipment scale and number under risk. A simulation model was developed and used to predict the available field operation time for machinery as a function of weather and soil moisture content (Babeir et al. (1986). Gao and Hunt (1985) developed a model based on power requirement for self-propelled machinery selection which is an extension of the previous approach by Hunt (1977).

2.5.4 **Machinery selection and weather risk**

Simulation models have been employed to aid farm management decisions under conditions of uncertainty (Halter and Dean, 1965; Zusman and Amotz, 1965). Many studies have extended research into the area of decisions by involving machinery capacity in the use of different mathematical programming models and simulation (Donaldson, 1968; Sorenson and Gilheany, 1970; Danok et al. 1980) under risk caused by uncertain weather conditions, timeliness penalties on yield losses, and decision maker's attitudes towards risk aversion.

There have been a number of other authors besides Hunt (1977) who have used the least cost approach to optimum farm machinery selection. They used weather data in their calculation of timeliness (Donaldson, 1968; Frisby and Bockhop, 1968; Hughes and Holtman, 1976; Tulu et al. 1974). Chancellor (1969) used a number of mathematical formulae to calculate the optimum sized tractors and concluded that costs increase more quickly if one is underpowered than if it is overpowered. Burrows and Siemens (1974) calculated optimum machinery for various sizes of maize soybean farms. McIsaac and Lovering (1976) developed a computer program to calculate the least cost implement sizes in the tillage and seeding of cereals. O'Connell et al. (1978) presented a model for least cost sizing of machinery operations in Eastern Washington. Russell and MacHardy (1970) reported that grain harvesting in Western Canada is a weather dependent operation. The slower an individual farmer completed his combine harvesting, the greater was the risk. To avert the risk penalty, the speed of a big combine harvester should be increased in harvesting operations. A total fixed cost and penalty cost per hectare for an operation period is determined by adding the penalties to the fixed costs. The cost time curve calculated will be independent of area (MacHardy, 1966a; 1966b).

Hazel (1971) suggested that quadratic programming is a useful method to consider gross margin uncertainty in farm planning. In many machinery selection studies, the main objective has been assumed to be the completion of certain field operations before a given set of dates at a minimum total cost (Hughes and Holtman, 1976; Ozkan and Frisby, 1981b). Other authors have estimated an economic penalty which farmers pay indirectly, when critical field operations such as planting and harvesting are not completed within an optimum period (McIsaac and Lavering, 1976). Farm machinery selection is influenced by the farm manager's goal and objectives, financial ability to assume risk and the size of the possible gains or losses from the decision (Nelson et al. 1978).

Brink and McCarl (1978; 1979) studied risk modelling and have outlined procedures whereby risk aversion can be incorporated into the model. There are several methods available to determine the set of risk efficient management strategies, given the associated net returns. One method of selecting machinery under risk is to use a mean variance analysis (Hazel, 1971). It is used to determine the risk efficient set of equipment.

Danok et al. (1980) quoted that weather affects farm production and profitability in various ways, but the effect most directly associated with machinery selection is uncertainty in the time available for field work. Elderen (1981) described three aspects of the tactical planning of operations which are considered as:

the performance of men and machines in completing the task;
the sequences of operations on different fields of a crop;
the weather and its influence on crops, soil moisture and the workability of operations.

Brown (1981) reported that increased machinery capacity can decrease the risk of crop losses by making sure that the crop is planted and harvested on time. The amount of time needed depends on the size of farm operation, the type of crop grown and their associated operations, the type of rotation used, the size, speed and efficiency of the machinery utilised, the labour force and the soil texture. The time available depends on the weather. Available field work for an operation depends on the appropriate calendar period within each week. The number of days suitable for field work depends on the weather and can be determined for different probability levels (Eradat Oskoui, 1981; Elbanna, 1986).

Whitson et al. (1981) used a model to maximise returns to the fixed resources of a farm given the limitation of land, hours of available time under weather risk, and machinery characteristics. Farmers seldom buy a complete set of new machinery at the same time. More often they buy one or two new machines and try to size them to fit the existing system depending on the environmental conditions (Rotz et al. 1983). Audsley (1984a) used weather uncertainty to select machinery for autumn operations. McClendon et al. (1987) reported that an inadequate equipment capacity can extend spring land preparation and planting time to the point that crop maturity may be delayed. Ozkan and Edwards (1986) used in their model the expected minimum number of work days in six years out of eight (75% probability) based on the observations collected by Iowa Crop and Livestock Reporting Service since 1958. The model calculates the area capacity of each machine and determines how many field hours are needed to complete each operation. Then using the suitable work days information and the hours of field time available per day, the actual number of days needed to complete each operation is calculated.

2.5.5 Risk efficiency

There are several methods available to determine the set of risk efficient management strategies, given the associated risk returns. One general method of selecting machinery under risk is to use a mean-variance analysis. This approach can be tackled by a system of preference ordering based on the principles of stochastic dominance which was developed by Quirk and Saposnik (1962), reintroduced and extended by Hadar and Russell (1969) and by Whitmore (1970). The concept of stochastic dominance is clearly defined by the first and second order stochastic dominance. Taking any two risky prospects F and G with net income probability distribution functions f(x) and g(x) on the interval [a,b], the cumulative distribution functions are $F_1(x)$ and $G_1(x)$ (fig. 2.8). For those farmers who prefer more income to less if:

$$F_1(x) \leq G_1(x) \qquad \ldots\ 2.38$$

everywhere and if the inequality holds in at least one point $F_1(x)$ can be said to be dominant over $G_1(x)$ in the first degree. This is tantamount to visual separation with $F_1(x)$ everywhere to the right

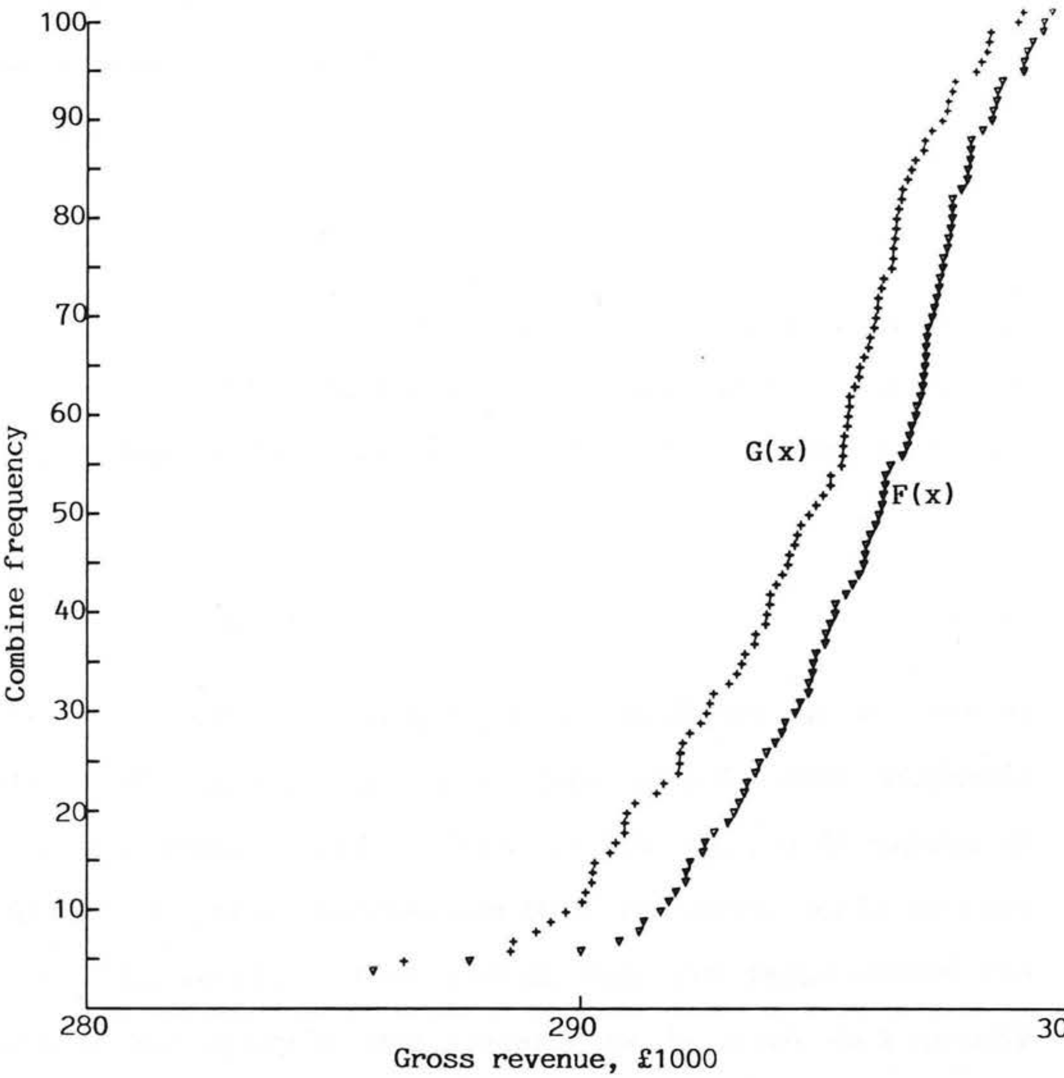

Fig 2.8 Stochastic dominance. First order ranking F over G

of $G_1(x)$ except where the two functions merge. At any given value of x the probability that F will exceed that level is greater than or equal to the probability that G will exceed that level. The mean value of x in F is greater than the mean value of x in G. Where cumulative distributory functions cross the second order condition may help to rank the prospects. By definition,

$$F_2(x) = \int_a^x F_1(x)\, dx \qquad \dots 2.39$$

and $$G_2(x) = \int_a^x G_2(x)\, dx$$

The area under the $F_1(x)$ curve is $F_2(x)$ and the area under $G_1(x)$ curve is $G_2(x)$. For those farmers who prefer more income to less and value income in the lower range more than income in the higher range:

$$F_2(x) \leq G_2(x) \qquad \dots 2.40$$

is sufficient to establish second order dominance of F over G (Fawcett et al. 1988). In fact, since second order stochastic dominance is a weaker condition than the first one, it is capable of ordering a larger set of distributions than that which can be ordered under the first order. It is obvious that any result within the framework of the theory of risk aversion can be established directly by means of second stochastic dominance. Conversely, any case of preference under risk aversion must imply second order stochastic dominance (Hadar and Russell, 1969). They introduced the concept to predict a decision maker's choice between given pairs of risky alternatives without having any knowledge of a decision maker's utility function except that it displays risk aversion. Porter and Gaumintz (1972) presented the results of several empirical studies of the similarities and differences between the mean-variance approach and stochastic dominance efficiency. They concluded from the results that, except for the highly risk averse investor, the choice between the mean-variance model and the stochastic dominance model for selecting efficient portfolios is not critical.

Meyer (1974) developed a more general form of stochastic dominance which allows one to predict a decision maker's choice between a pair of risky alternatives knowing only a lower and an upper boundary on his measure of risk aversion. Meyer (1974; 1977) indicated that stochastic dominance with respect to a function can be more efficient in ranking alternative strategies than first, second and third degree of stochastic dominance when the appropriate risk aversion intervals can be specified. Risk analysis by stochastic dominance is an alternative method by which the cumulative probability distribution functions of alternative management strategies can be compared to determine a preferred strategy under risk (Danok et al. 1980). Stochastic dominance provides an approach to machinery selection. Its analysis may be applied to choose a machinery set which is satisfactory in a given field time. Stochastic dominance is attractive in that it can reduce the set of risk efficient management strategies. It is a technique which has been applied to a number of agricultural settings to rank alternative depreciation methods (Richardson and Nixon, 1984), agricultural policy decisions (Kramer and Pope, 1981) and sorghum storage decisions (Rister et al. 1984). Stochastic dominance with respect to a function was used to rank four crop rotation strategies under different levels of producer risk aversion and discount rates (Lee et al. 1987).

An alternative to mean variance approach and stochastic dominance is Gini's Mean Difference analysis. The technique is also robust like stochastic dominance in terms of utility functional form. Buccola and Subbai (1984) compared mean-variance, stochastic dominance and Gini-Mean difference analysis. They stated that stochastic dominance methods have been used recently to derive efficient strategies for given risk aversion intervals. They used a new dimension approach which makes use of the Gini coefficient to express effectively the preferences of weakly risk averse individuals. An application is provided of farmer's choices among alternative co-operative pooling rules. Applied research in the economics of risk decision relies heavily on procedures for identifying stochastically efficient strategies. Yitzhaki (1982) proposed an alternative decision model in which risk is reflected by a function of the mean absolute difference. The technique has some of the covariance of mean-variance analysis and is robust like stochastic dominance with respect to utility and probability form. A risk averse manager may select larger machinery capacity in order to accommodate situations with low numbers of available field work days.

For this study, the branch and bound algorithm seemed to be suitable for mixed integer solutions to the farm machinery selection problem. Machinery sets are selected simultaneously with the chosen cropping pattern on a given land area. Field operations take place in discrete time periods during which available work days are distinguished by optimal sowing date and an optimal harvest date. The expected field performance of the chosen sets is simulated via the sequence of available work days. Based on weather records for a specific site, a long term run of work days can be generated by using a simulation model. To distinguish between alternative solutions of linear programming, stochastic dominance as a technique can be used to rank the cumulative probability distribution of expected farm income resulting from the operation of each selected machinery set. Timeliness penalties are introduced as additional criterion to distinguish between feasible solutions.

2.6 Present annual cost

A simple estimate of machinery operating costs can be obtained by averaging the annual cost over the full period of ownership. This average cost, however, does not reflect any variation in annual operating costs with age of the machine, nor does it account for the changing value of money over the period of ownership. For a more accurate appraisal of complex agricultural machinery management problems, the present annual machinery ownership costs can be calculated using the actual cash flows which occur each year. Three types of cash flow are involved in the calculation of the annual cost of a machine:

(1) the capital cost with interest charges repayable by equal mortgage instalments;

(2) the recurring annual repair and insurance charges;

(3) the income from selling the machine.

These discounted cash flows form the basis of a machinery cost model devised by Audsley and Wheeler (1978) and further developed by Witney (1985, 1988) and Elbanna (1986).

The Edinburgh Machinery Cost Model includes the effect of loan rate and loan period on the interest charges incorporated in the mortgage payments; the effect of capital allowances, taking account of the actual balancing charges at the end of the period of ownership; and the effect of tax relief on the interest charges, repair costs and insurance premiums. These refinements provide a more accurate annual cost which, in turn, facilitates the calculation of the optimum ownership period. Machinery replacement is most economic when the present annual ownership cost reaches a minimum value which is numerically equal to the marginal holding cost.

2.6.1 Costing procedures

Discounted cash flows are used to determine the current total cost in money of the same value. The essence of the discounting procedure is that present money is worth more than future money; the further ahead that the money is to be received in the future, the less it is worth in present-day terms. The reasons for this are two-fold: firstly, the further ahead that money is promised, the more risk that it may not materialise; secondly, cash received today can be invested to be worth more in the future. These reasons are valid even when the purchasing power of money remains constant but the effects of inflation can also be included in the calculation of actual cash flows.

Annual repayment of loan capital and interest

The capital cost of a machine, PP, may occur as a payment (outward cash flow) at the beginning of ownership at time zero, or else the machine may be bought by borrowing the money and paying a series of equal annual mortgage payments, M_m:

$$M_m = PP\ i_1(1 + i_1)^N/[(1 + i_1)^N - 1] \qquad \ldots\ 2.41$$

where i_1 is the loan interest rate and N is the period of ownership

(Audsley and Wheeler, 1978). It is assumed that the period of the loan is the same as the period of ownership. Payment of one's own capital may be thought of as borrowing from oneself at an interest rate which is usually lower, but which occasionally could be higher compared with special rates offered by machinery companies to promote sales. Thus, the concept of opportunity cost of capital may also be included.

The discounted cash flow or present annual cost of a cash flow, CF, in the year, n, is the amount of money, NPV, which must be invested now to pay for the cash flow in the n^{th} year. If the interest on investments is i_i, then:

$$NPV = \quad CF_n/(1 + i_i)^n \qquad \ldots\ 2.42$$

For a series of equal annual cash flows, M_m, over the life of the machine, the total present mortgage cost, NPV_m, is:

$$NPV_m \quad = \quad M_m \sum_{n=1}^{N} \quad 1/(1 + i_i)^n \qquad \ldots\ 2.43$$

By rearranging terms and combining with Eqn 2.41, the total present mortgage cost becomes:

$$NPV = \quad PP \ \frac{i_l(1 + i_l)^N[(1 + 1_i)^N - 1]}{i_i(1 + i_i)^N[(1 + i_l)^N - 1]} \qquad \ldots\ 2.44$$

This is the investment needed at the start of ownership which pays for all the annual payments. If the interest rate on investments is the same as the loan interest rate, the total present mortgage cost is equivalent to the purchase price.

Recurring annual repair and insurance charges

For an annual repair cost, R_n, in the n^{th} year of machine ownership, and insurance charged at one per cent of the resale value of the machine at the end of the previous year, $S_{(n-1)}$, the present annual cost for repairs and insurance, NPV_r, is:

$$NPV_r = \sum_{n=1}^{N} [R_n + 0.01\ S_{(n-1)}]w^n \qquad \text{... 2.45}$$

where the inflated discount factor, w, is:

$$w = (1 + j)/(1 + i_i) \qquad \text{... 2.46}$$

and j is the rate of inflation. For the calculation of all the present annual values, the rate of inflation and the interest rates for loan and investment are assumed constant throughout the period of investment.

Income from selling the machine

When the machine is bought new, the current resale value of an equivalent, 'N' year old machine is S_N, so the resale value in 'N' years time will have changed with inflation. The present resale value, NPV_S, after discounting is:

$$NPV_S = S_N\ w^N \qquad \text{... 2.47}$$

Tax relief

Various machinery costs are eligible for tax relief, namely, annual capital allowances, interest payments, repair and insurance charges, and fuel and oil costs. These allowances only benefit those farmers who make sufficient profit to pay tax - the more profitable the business, the higher the marginal rate of tax and the greater the financial advantage from the allowances.

For taxation purposes, the annual rate of capital allowance in 1987 is 25 per cent on a diminishing balance basis, that is on the written-down value of the machine. Thus, the annual capital allowance for an 'n' year old machine, CA_n, is:

$$CA_n = 0.25\ PP\ (1 - 0.25)^{(n-1)} \qquad \ldots\ 2.48$$

When repaying the purchase price by means of a mortgage in equal instalments, the initial instalments largely comprise interest whilst later instalments are mainly repayment of the principal. The annual interest charge, I_n, is given by the interest on the outstanding balance of the loan after repayment of the mortgage instalments in the preceding period of the loan:

$$I_n = PP\ i_1[(1+i_1)^N - (1+i_1)^{(n-1)}]/[(1+i_1)^N - 1] \qquad \ldots\ 2.49$$

Repair and insurance costs have already been determined previously (Eqn 2.45) and fuel costs can be considered separately as they are already in present value terms.

Once the machine is eventually sold, or traded in, the total capital allowance must be adjusted to equate with the actual loss in value of the machine during the period of ownership. If the resale value exceeds the written-down value used for tax assessment, then it is necessary to have a balancing charge on which tax must be paid. This balancing charge in the last year of ownership, BC_N, is:

$$BC_N = \sum_{n=1}^{N} CA_n + S_N - PP \qquad \ldots\ 2.50$$

Alternatively, if the resale value is less than the written-down value, then there is a balancing allowance (i.e. a negative balancing charge) on which additional tax relief is available.

The net present value of the capital allowances, the interest charges and the balancing charge, NPV_t, is given by:

$$NPV_t = \sum_{n=1}^{N} (CA_n + I_n)/(1 + i_i)^n - BC_N/(1 + i_i)^N \quad \ldots\ 2.51$$

In practice, the tax relief on capital allowances, interest payments, repair and insurance charges, and fuel and oil costs accrue in the year following that to which they apply and the balancing charge or allowance is deducted from or added to the capital allowances on other machines within the farm equipment 'pool'. For the appraisal of an individual machine, however, it was considered expedient to allocate these adjustments to the year to which they refer, so that the calculation of machinery cost remains within the ownership period.

The various tax allowances are multiplied by the marginal tax rate, t, to give the tax relief. There is a series of taxable income bands, each with its own tax rate, ranging from the standard tax rate of 27 per cent in 1987 up to 60 per cent at higher levels of taxable income. The annual tax relief is deducted from the gross cash outgoings to give the net amounts for discounting.

Present annual ownership cost

The present annual ownership cost with tax relief, A_t, is the value in today's money of 'N' equal value, annual payments made during the ownership of the machine. These annual payments are again influenced by inflation and discounting, so that combining the three cash flows from Eqns 2.43, 2.45 (adjusted for tax), and 2.47 together with the tax allowances from Eqn 2.51

$$A_t \sum_{n=1}^{N} w^n = NPV_m + (1-t)NPV_r - NPV_s - t\ NPV_t \qquad \ldots\ 2.52$$

Since it can be shown that:

$$\sum_{n=1}^{N} w^n = w(w^N - 1)/(w - 1) \qquad \ldots\ 2.53$$

the final form of the equation for the present annual ownership cost is:

$$A_t = [NPV_m + (1-t)NPV_r - NPV_s - t\ NPV_t](w-1)/[w(w^N-1)] \ldots 2.54$$

2.6.2 **Machinery costs**

Machinery costs have been traditionally defined as fixed costs and variable costs. Fixed costs include depreciation, interest, insurance and housing - all more readily determined and analysed than variable costs. Hunt (1977) defined the variable costs of a machinery system as 'those costs which increase proportionally with the amount of operational use' and included repairs and maintenance, fuel, and labour costs in this category.

<u>Depreciation</u>

Even before a machine has been purchased, it is necessary to estimate its resale value so that the investment costs can be identified. Depreciation is defined as the loss in value and service capacity arising from wear in use, obselescence, accidental damage and corrosion. Although depreciation is commonly estimated by the straight line method or by the declining balance method, neither technique adequately represents the rapid depreciation which occurs in the early years of the ownership period. The accuracy of the declining balance method is improved by adopting a logarithmic function but it is proposed that the residual discontinuities are effectively eliminated by an approach which Witney (1985) identified as 'decremental depreciation'.

Logarithmic depreciation

Peacock and Brake (1970) predicted the trade-in values of some machines by means of both linear and logarithmic functions of their age. Using the logarithmic form, the current resale value of an 'n' year old machine as a decimal proportion of the current initial purchase price is:

$$S_n/PP = SA\ SB^n \qquad \dots 2.55$$

where SA = first year correction factor;
SB = annual depreciation factor.

American machinery is classified into four groups for estimating the resale value and the relevant factors are listed in Table 2.3 (ASAE, 1986). The use of the first year correction factor is not the complete answer because the improved approximation in later years is offset by the error in the resale value of a near new machine.

Decremental depreciation

Ayres and Waizencker (1978) proposed that the resale value of an 'n' year old vehicle is related to the current purchase price of an equivalent new vehicle by an inflation proof expression:

$$S_n/PP = e^{(-k1\ n)} \qquad \dots 2.56$$

Table 2.3 Values of the first year correction factor and the annual depreciation factor for calculating the resale value of various machines

Machine	First year correction factor (SA)	Annual depreciation factor (SB)
Tractors	0.68	0.920
Combine harvesters, self-propelled swathers	0.64	0.885
Balers, forage harvesters, blowers, self-propelled sprayers	0.56	0.885
All other field machines	0.60	0.885

where e is the base of the natural logarithms and k_1 is an exponent depending to some extent on vehicle type.

Based on this method, Hagger (1986) analysed resale prices of eight makes of two-wheel drive and four-wheel drive tractors available in the UK and combine harvesters. As only limited resale data is available for current models, preference was given to past models using prices from the Market Guide produced by the British Agricultural and Garden Machinery Association Ltd. The historical price data was updated to current monetary values by means of price indices (Elbanna and Witney, 1986). The values of the resale exponent, k_1, for two-wheel drive tractors, four-wheel drive tractors and combine harvesters are shown in Table 2.4. Although there is some variation in the values of the resale exponents for the various machines and between different makes of tractors, a single value for the resale exponent, k_1, of 0.21 explains 97 per cent of the variation.

Repair costs

Repair and maintenance are the most important components of machine operating costs. These are proportional to the amount of use of the equipment. There is probably less known about repair charges than any other item of machinery cost. Few records of machinery repair costs are sufficiently accurate to identify individual machine charges. Repair costs may be separated into two parts: firstly, the cost of a repair including the cost of labour and, secondly, the cost of delay in field operations due to machine "down time", only the former being considered in this analysis. Normal wear deterioration is directly related to use. The nature of failure on deterioration such

Table 2.4 Depreciation parameters for different models of 2WD and 4WD tractors, and combine harvesters First order (k_1)

Machine type	Parameter k_1	Standard dev of k_1	Degree of freedom	% explained
ALL TRACTORS	0.21	0.00167	440	97.31
ALL 2WD TRACTORS	0.20	0.00167	297	98.01
ALL 4WD TRACTORS	0.24	0.00312	142	97.62
COMBINE HARVESTERS	0.22	0.00240	183	97.84
2 WD TRACTORS				
Massey Ferguson	0.19	0.00308	95	97.57
Ford	0.19	0.00241	82	98.73
Case International	0.21	0.00531	18	98.86
Zetor	0.21	0.00596	20	98.43
John Deere	0.22	0.00432	29	98.87
Deutz Fahr	0.22	0.00582	13	99.08
Fiat	0.22	0.00431	27	99.01
Renault	0.23	0.02125	6	95.27
4 WD TRACTORS				
Massey Ferguson	0.23	0.00758	33	96.55
Ford	0.25	0.01901	9	94.99
Case International	0.26	0.00553	13	99.43
Zetor	0.23	0.00550	20	98.88
John Deere	0.25	0.01023	18	96.97
Deutz Fahr	0.23	0.01068	7	98.48
Fiat	0.24	0.00666	25	98.06
Renault	0.25	0.00959	10	98.52

that repair service is needed for equipment, appears to be a random variable with time, therefore changing a certain percentage of the initial cost each year is justified only when a machine is kept for its entire service life (Fairbanks et al. 1971). Despite the complexity of the problem, the mathematical analysis of repair costs and the probabilistic prediction of the frequency of occurrence of a breakdown have been approached by many researchers. Thus, repair costs can be defined by probability laws. The probability distribution can be used to estimate the frequency of breakdowns which is difficult to predict because breakdowns occur in different time intervals but it is possible to determine repair costs by using linear or non-linear functions. Chancellor (1968), after an extensive examination of repair cost data, concluded that the repair costs for a machine depend on its initial price, its engine power and hours used. Laing and Link (1970) analysed the seven standard equations developed by Larson and Bowers (1965), to build a maintenance scheduling programme in which:

$$TAR = RA[X]^{RB} \qquad \ldots 2.57$$

where TAR = total accumulated repairs and maintenance, % of initial price;
RA, RB = repair coefficients;
X = accumulated use, 1000's of hours.

Bowers and Hunt (1970) surveyed 900 farmers to obtain repair cost information as a function of machine age and use. Fairbanks et al. (1971) conducted a survey of 114 farm managers within the Kansas area to collect repair cost data on tractors and combines to derive a general formula for repair costs. Farrow et al. (1980) also analysed repair cost data for several farms on the Pacific Coast. They found their data similar to that collected by Bowers and Hunt (1970) and

Hunt (1974b). The values of the repair constant and repair exponent for different machines are given in Table 2.5. When modelling individual field operations, the field speed at which the machine is operated influences the repair and maintenance cost. A machine which is operated at a faster speed will be used for fewer hours, and therefore have a lower cost. The problem only occurs when the cost of a particular field operation is modelled because field speed will have an unrealistic influence on the cost. Rotz (1985) stated that, when modelling on a field operation level, the accumulated repair cost equation should be extended to include a function of field speed. Machine age would be defined as the product of hours of use and field speed to give the following relationship:

$$TAR = RA\ [X\ V_1/V_o]^{RB} \qquad \dots\ 2.58$$

where: V_1 = operational speed of machine, km/h;
V_o = recommended field speed, km/h.

The proposed model parameters provide more consistency in the predicted repair and maintenance costs across machine types than was obtained with previous models and parameters. Since machine age is modelled as hours of operation rather than field area covered, more realistic costs are obtained across a wide range of machine sizes and ages.

The wear-out life used in the total accumulated repair cost was 12000 hours for tractors. This was a nominal value selected from collected data (Bowers and Hunt, 1970; Hunt, 1971; ASAE, 1972). Ward et al. (1985) suggested that the real wear-out life of a tractor is somewhat less than 12000 hours. However, they stated that a total

Table 2.5 Values of the repair constant and repair exponent used in the calculation of accumulated repair costs for various types of machine

Machine type	Av field speed, km/h		Estimated life, h	Total life repairs, % of list price	Accumulated repair cost index	
	Typical	Range			Repair constant	Repair exponent
TRACTORS & TRANSPORT						
Two-wheel drive			10000	120	0.012	2.0
Four-wheel drive and Crawler			10000	100	0.010	2.0
Trailer			3000	80	0.19	1.3
TILLAGE						
Mouldboard plough	7.0	5.0-10.0	2000	150	0.43	1.8
Heavy-duty disc	7.0	5.5-10.0	2000	60	0.18	1.7
Tandem disc harrow	6.5	5.0-10.0	2000	60	0.18	1.7
Chisel plough	7.0	6.5-10.5	2000	100	0.38	1.4
Field cultivator	9.0	5.0-13.0	2000	80	0.30	1.4
Spring tooth harrow	9.0	5.0-10.0	2000	80	0.30	1.4
Roller-packer	10.0	7.0-12.0	2000	40	0.16	1.3
Rotary hoe	11.0	8.0-16.0	2000	60	0.23	1.4
Rowcrop cultivator	5.5	4.0- 8.0	2000	100	0.22	2.2
Rotary cultivator	5.0	2.0- 7.0	1500	80	0.36	2.0
ESTABLISHMENT						
Fertiliser spreader	7.0	5.0- 8.0	1200	120	0.95	1.3
Grain drill	6.5	4.0-10.0	1200	80	0.54	2.1
Crop sprayer	10.5	5.0-11.5	1500	70	0.41	1.3
HARVESTING						
Combine harvester:						
trailed	5.0	3.0- 6.5	2000	90	0.18	2.3
self-propelled	5.0	3.0- 6.5	2000	50	0.12	2.1
Mower	8.0	6.5-11.0	2000	150	0.46	1.7
Mower conditioner	7.0	5.0-10.0	2000	80	0.26	1.6
Side delivery rake	7.0	6.5- 8.0	2000	100	0.38	1.4
Baler	5.5	4.0- 8.0	2000	80	0.23	1.8
Big bale baler	5.5	5.0- 8.0	2000	80	0.23	1.8
Forage harvester:						
trailed	4.0	2.5- 4.0	2000	80	0.23	1.8
self-propelled	5.0	2.5-10.0	2500	60	0.12	1.8
Forage blower			2000	50	0.14	1.8
Sugar beet harvester	5.0	4.0- 8.0	2500	70	0.19	1.4
Potato harvester	3.0	2.5- 6.5	2500	70	0.19	1.4

accumulated use of 65% (8000 hours) is a more realistic estimate of the actual wear-out life of tractors.

Hunt and Fijii (1976) analysed eight years data, collected from 45 Illinois farms, which included 740 tractors and implements to evaluate the magnitude of repair costs and frequency of their occurrence. These results were reported as a percentage. Abdelmotaleb and Marley (1987) quoted that repair costs are an important portion of the total cost of owning and operating farm machinery and are highly variable and difficult to predict. A survey has been developed to collect current data on the costs of repair and maintenance of tractors and combines from a sample of Iowa farmers. These data were used to examine the previous formulae which are used by the ASAE, and to test their degree of accuracy. They concluded also that the average tractor and combine harvester life estimated by the farmers were 9000 hours and 3000 hours, respectively.

Replacement decision

An ownership problem with any farm machine is when to replace it with a new or more modern machine. The two basic reasons to replace machines are: when they cease to function or when they cannot provide service as economically as a replacement. As reliability and amount of repairs go hand in hand, both can be related to the initial cost, quality of the machine, number of hours of annual use and age. The replacement policy frequently adopted by fleet owners is to replace a vehicle at a certain time. Jardine et al. (1976) stated that replacement should occur when it is cheaper in the long run to purchase a new vehicle than to maintain the old one. This point or decision will vary from vehicle to vehicle, since each one has its own "good or bad" characteristics which are reflected in their maintenance costs. Peterson and Milligan (1976) reported that replacement decisions are based on determining the economic life which is the time-span beginning at the optimum acquisition age and ending at the optimum retirement age of the asset. A graphical method, in terms of rate of holding cost, was used by Dunford and Pickard (1961) to determine an optimum replacement time for agricultural machinery. Scarborough and Hunt (1973) developed a procedure based on the method utilized by Bowers and Hunt (1970) and originally proposed by Larson and Bowers (1965) to obtain the optimum replacement time for machinery. Boyce et al. (1976) describe the most economical time to replace a machine in a method based on discounting the cash flows which are incurred when a machine is purchased, used and resold. The discounted cash flow can be presented as an annual equivalent cost and the machine should be replaced at a time when this cost is a minimum. Ayres and Waizeneker (1978) used the concept of economic life and analysed the data collected at the London Borough of Hammersmith to develop a simplified approach to vehicle replacement. Hunt (1977) pointed out that the time of replacement decision depends on the accumulated costs over a period of years. He compares yearly costs and accumulated costs during the life of a machine.

Fuel and oil costs

The fuel consumption of a diesel engine in a tractor or self-propelled farm machine is governed by the amount of energy demanded at the drawbar or at the power take-off. Fuel efficiency varies with engine loading and reaches a maximum at about 90 per cent of full power. In order to compensate for this variation in fuel efficiency (ASAE, 1982), the specific fuel consumption of a diesel engine is related to the power utilisation ratio, RU, such that:

$$FC = 2.64\ RU + 3.91 - 0.2\sqrt{(738\ RU + 173)} \qquad \ldots\ 2.59$$

where: FC = specific fuel consumption, l/kW h;

$$RU = \frac{\text{equivalent power take off power requirement, kW}}{\text{maximum power take-off power, kW}}$$

For tractor operations throughout the year, the average power utilisation ratio is 0.55.

Oil consumption is defined as the volume of engine crankcase oil replaced at the recommended change intervals. For simplicity, the oil consumption, OC, is related to the rated engine power, P_{max}, without any adjustment for engine loading (ASAE, 1986):

$$OC = 0.02169 + 0.00059\ P_{max} \qquad \ldots\ 2.60$$

2.6.3 Operating costs

The annual use of a tractor is taken as 1000 hours per year. The age of the machine can be adjusted to take account of the level of use, a highly used machine having a lower depreciation age than a heavily used (Witney, 1985). Kerr (1986) carried out a survey on the use of tractors on East Midlands Farms in which he concluded that the average hours worked by tractors per annum is considerably less than 900 hours previously assumed and so it would appear that the standard figure should be reduced by at least a third. His survey was based on 814 tractors. He quoted also that tractors developing between 50 and 80 kW are the main work-horses on farms of all sizes and they average more hours of work per annum than any other power group. Zoz (1974b) calculated in his model the individual cost items. As an input data, he listed that the tractor is used 400 hours per year, exclusive of ploughing. Ploughing hours are added to obtain the total. The life of a tractor is 7000 hours or 10 years. Cottrell and Audsley (1976) disagreed and stated that ploughing was allocated 200 hours per annum which is the maximum time allowed for a tractor life of 5 years with 600 hours for other work. From a recent survey, however, very high powered four-wheel drive tractors are mainly used for cultivation work and may do as little as 350 hours per year. It was pointed out by Elbanna (1986) that the annual cost of an implement depends on its size and hours used for a farm operation. This is due to the tractor implement performance and their work rate to cover a specific area. The faster the speed of operation, the less the machine hours used and so the lower the accumulated repair costs. Rotz (1985) proposed a standard model for agricultural machinery repair costs which always provides reasonable results that are consistent across different types and sizes of machines and for varying amounts of machine use. He stated that it is impossible to create a precise model for repair and maintenance costs since they are stochastic in nature. The accumulated repair cost equation should be extended to include a function of field speed.

More complex functions of width and speed were developed to predict the purchase prices of mouldboard ploughs (Zoz, 1974b). This same procedure was adopted for chisel ploughs (Cottrell and Audsley, 1976), whilst the prices of rotary diggers were influenced by a cubic term of power related to linear function of machine width. The reason for the inclusion of a speed related price coefficient appears to have been influenced by the application of the price functions which affect width and speed on least cost tillage.

More realistically, it will be the effect of greater speed reflected in higher repair costs (Rotz, 1985) which is determined as an increasing proportion of machinery operating costs. Subsequently, a satisfactory correlation of mouldboard plough prices was obtained as a linear function of number of furrows (Witney and Eradat Oskoui, 1982). Data was collected on the list prices of a wide range of farm machines, including two-wheel drive, front-wheel assist, four-wheel drive tractors (Anon, 1977 and 1983b), mounted/semi-mounted conventional and reversible ploughs equipped with either fixed or auto reset legs (Anon, 1980 and 1983a). Initial price equations for these machine types were developed using regression analysis (Elbanna and Witney, 1986). The tractor purchase prices were found to be linear functions of the maximum power take-off (Elbanna and Witney, 1986):

$$PP_t = a_t + b_t P_{PTO} \qquad \ldots\ 2.61$$

where PP_t = tractor purchase price, £;
a_t, b_t = price coefficients depending on tractor type;
P_{PTO} = maximum power take-off, kW.

Machinery purchase prices were linearly related to their major components, such as the number and spacing of bodies; the plough price equation is defined as (Elbanna and Witney, 1986):

$$PP_p = a_p + b_p w_b + c_p N_b \qquad \ldots\ 2.62$$

where a_p, b_p, c_p = price coefficients;
N_b = number of plough bodies;
w_b = width of furrow, mm;
PP_p = price of plough; £.

Zoz (1974b) calculated a least cost tillage for an optimum width and speed, The optimum point is determined and contours of equal cost can be plotted. He shows in Fig 2.9 an example of the program output using the following variables as input data: tractive efficiency ratio = 0.70; dynamic ratio = 0.50; travel reduction 15%; dynamic weight transfer = 0.45; PTO to axle hp ratio = 0.967; plough depth = 8 inches (20 cm); field efficiency 0.90; tractor life = 10 yr; plough life = 10 yr; interest rate 8%; salvage value = 10% of the purchase price after useful life is complete. For this set of variables, the minimum cost per acre was determined to be at 6.4 ft width and 5.2 mph. Other values such as 125 PTO hp, 3.6 acres per hour, approximately five 16 in bottoms. The minimum cost was $3.38 per acre. He noted that it is interesting to state that 200 PTO hp at 8 mph can have total costs equal to 100 PTO hp at less than half this speed. This is due to the small change in operating costs. Ozkan and Frisby (1981a) developed another model to minimise the overall energy efficiency of multi-crop farms by selecting the optimum power level and matching the correct implements.

Witney and Eradat Oskoui (1982), and Elbanna (1986) demonstrated the feasibility of a comprehensive computer model for the selection of economically variable tractor-plough combinations, by predicting traction, plough draught and available work days for a given climate and soil type within machinery, labour and timeliness penalty cost framework.

In this study, four tractors have been selected by the tractor

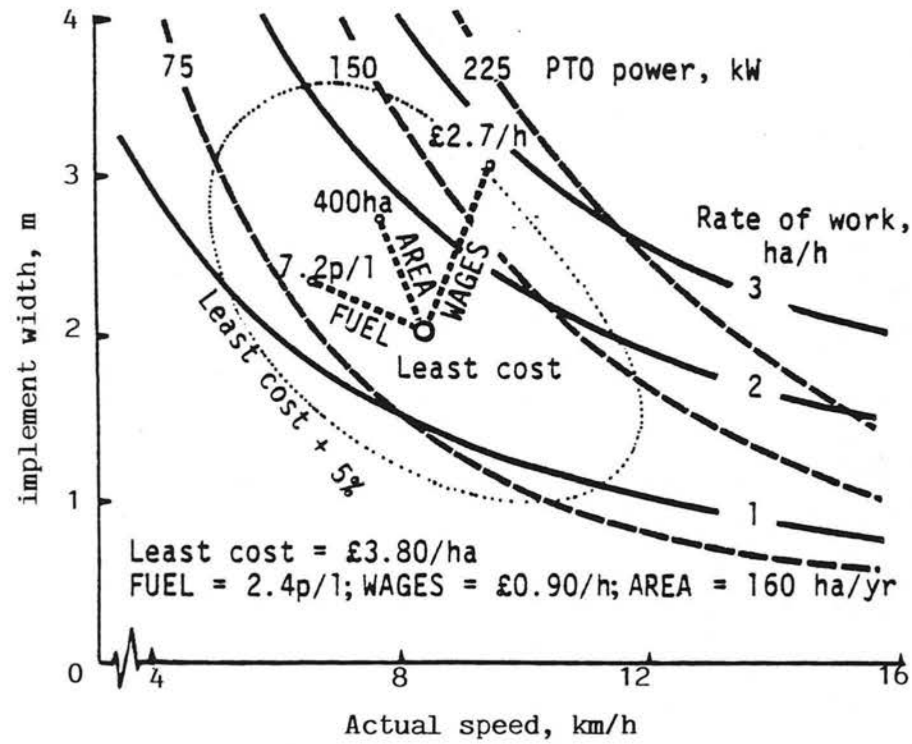

Fig 2.9 The effect of machine size and speed on ploughing costs (after Zoz)

implement combination model. The annual machine use is determined by linear programming solutions depending on the operations of a chosen rotation and the available workdays. The number of annual hours used depends also on the size of fleet used in the farm - the higher the number of machines performing the same task, the less hours used. The calculation of machinery costs cannot be determined without the knowledge of the number of annual hours used by a particular machine.

3. TECHNICO-ECONOMIC SELECTION OF TRACTOR/PLOUGHS

3.1 Costing model

The procedure used in machinery costing routine (Appendix A1) is based on the calculations of an annual cost with tax allowances. It consists of an examination of machinery prices, repair and maintenance costs, resale value, capital allowance, balancing charge, interest charges, and the effect of inflation and taxation on the investment. During the machine ownership period, an annual tax allowance is available to the owner each year. When the machine is sold, the establishment of a balancing charge or allowance is calculated depending on the written-down value of the machine. If the written-down value is negative, a balancing allowance is refunded, but if the value is positive, a balancing charge is made. The model has been extended by the calculation of the correct optimum ownership period which is graphically presented as the intersection of the minimum value of an annual cost and the marginal holding cost. The intersection value ensures the precise identification of the optimum replacement time even where the present annual curve is very flat with respect to the age of the machine. It serves also to emphasise the critical importance of accurate input data. In view of the paucity of information on depreciation and repair charges, the effect of their variation on the ownership period is investigated by means of a sensitivity analysis.

3.1.1 Resale value

Depreciation is a method of estimating the resale value. A first degree method of decremental depreciation has been used to determine the resale value for different makes of UK tractor (see Section 2.6.2). A single value of the resale exponent explains the high percentage of variation for more tractors and combine harvesters. Despite this high percentage of explanation, close investigation reveals that the resale value tends to be over-estimated for one and two year old trade-ins for which data is sparse (Fig 3.1). A rogue machine or damaged machine which could be sold is likely to have a low resale value. Equally, there is no data for resale at year 0 which is the same time of the year the machine was bought, and it would not be possible to get 80% of the new price for a brand new tractor resold one day after initial purchase. In this study the list price is used to calculate the resale value, but in reality there are substantial discounts offered by the seller of up to 10% off the list price. If the discount could be taken into account, it would be in better agreement in years 1 and 2. Elimination of this error involves the inclusion of a second degree exponent (Witney and Saadoun, 1986):

$$S_n/PP = \exp(k_1 n + k_2 n^2) \qquad \ldots\ 3.1$$

where
- S = resale value, £;
- n = machine age, yr;
- pp = purchase price, £;
- k_1, k_2 = resale exponents.

Figure 3.1 shows that best fit logarithm and best decremental resale values are similar for year 4 onwards but the best fit logarithm is not the accepted value.

The individual values of the two resale exponents are also listed in Table 3.1.

The age of the machine, n, can be adjusted to take account of level

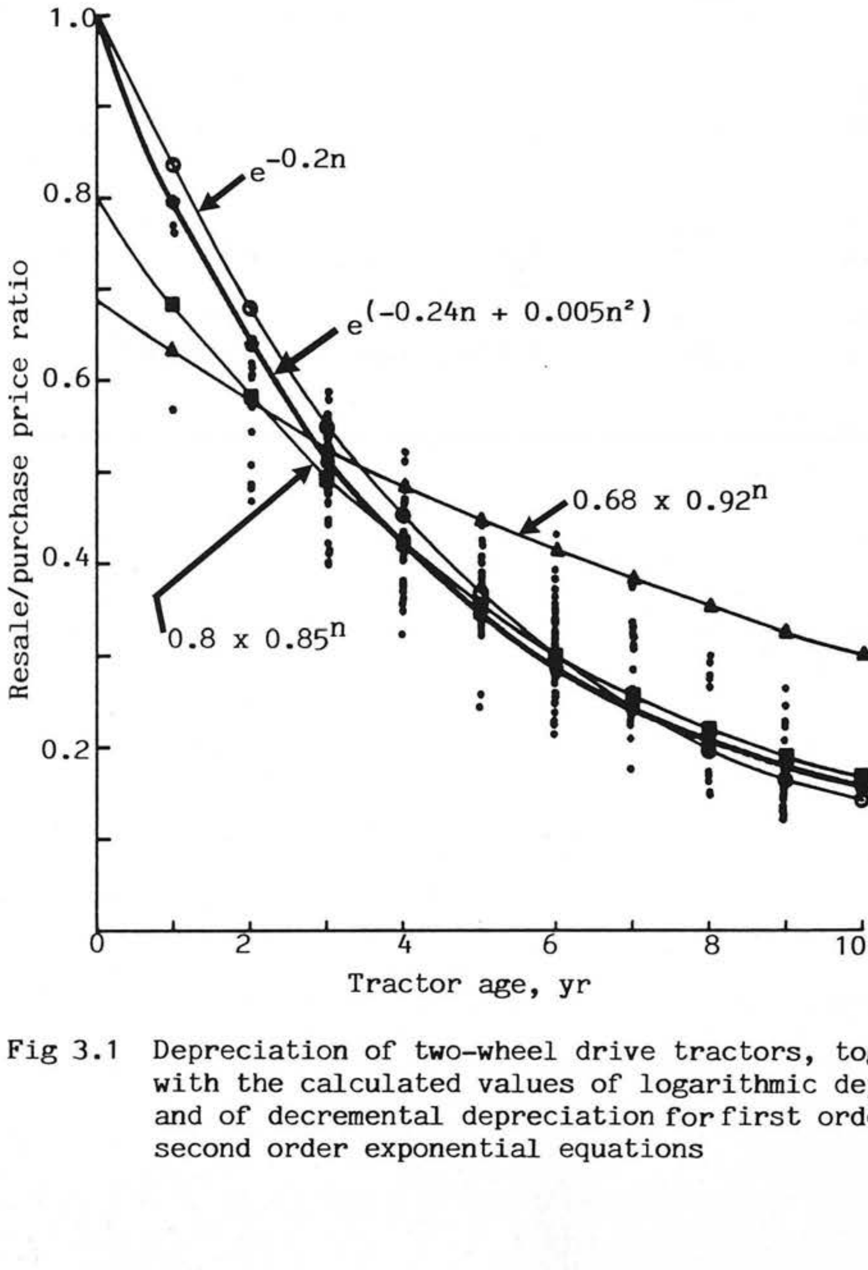

Fig 3.1 Depreciation of two-wheel drive tractors, together with the calculated values of logarithmic depreciation, and of decremental depreciation for first order and second order exponential equations

Table 3.1 Resale parameters for first order (k_1 only) and second order (k_1 and k_2) equations for two-wheel drive tractors, four-wheel drive tractors and combine harvesters

Machine type	Resale exponents [st dev] k_1	Resale exponents [st dev] k_2	Degree of freedom	Explanation of data, %
All 2WD tractors	0.20[0.0017]	-	298	98.01
	0.24[0.0070]	0.005[0.0010]	298	98.01
All 4WD tractors	0.24[0.0031]	-	142	97.12
	0.28[0.0108]	0.007[0.0016]	142	97.89
Combine harvesters	0.22[0.0024]	-	190	97.84
	0.26[0.0094]	0.007[0.0013]	190	97.60

of use, a lightly used machine having a lower 'depreciation age' than a heavily used one. This depreciation age is the mean of the actual age and the operational age, the latter being the ratio of the accumulated use to the average annual use (Witney, 1985). If the average tractor use is assumed to be 1000 h/yr, for example, a four year old tractor working for 1500 h/yr is equivalent to an operational age of six years and the mean value or depreciation age is then five years.

As well as providing a better correlation with available resale prices than obtained by other methods, the advantage of decremental depreciation is that the resale value of the machine when new, at age zero, is identical to the current purchase price. This overcomes the discontinuities incorporated in other methods for calculating depreciation.

Apart from the review of the resale values, the other machinery costs for repairs, insurance, fuel, shelter are fully discussed in section 2.6, together with the procedure of calculating the present annual cost. A further development to the cost model is the calculation of marginal holding cost.

3.1.2 **Marginal holding cost**

The marginal holding cost represents the extra costs incurred by keeping a machine for an additional year. For a period of ownership of only one year, the marginal cost is equal to the present annual ownership cost. For longer periods of ownership, however, the extra cost is not solely derived from the additional year of ownership because the change in the term of the mortgage alters interest payments in earlier years as well. Thus, the determination of the marginal cost involves the calculation of two sets of annual cash flows, CFN and CFM, for two different periods of ownership both including and excluding the additional year, respectively. The marginal cost, MC_N, for the year N comprises the present annual value of costs for that year, together with the sum of the present annual values of the extra costs for each of the preceding years:

$$MC_N = \frac{CFN_N}{w^N} + \sum_{n=1}^{(N-1)} (CFN_n - CFM_n)/w^n \qquad \ldots 3.2$$

where MC = marginal holding cost, £;
CFM, CFN = annual cash flows for two different periods of ownership excluding and including an additional year, £;
w = inflated discount factor.

3.1.3 **Financial analysis**

The annual ownership costs were calculated for a 60kW two-wheel drive tractor with an initial price of £16000. This price was derived from the 1983 purchase price trend (equation 2.61).

The availability of official price indices simplifies the updating of prices on an annual basis. The price indices for tractors and machinery are listed in Table 3.2. It is possible to calculate the current value of any chosen machine with index-linking to current prices (Elbanna and Witney, 1986). For example, updating prices from 1983 to 1987 requires the following conversion:

$$PP_{87} = PP_{83} . I_{87} / I_{83} \qquad \ldots 3.3$$

where I_{83}, I_{87} = prices indices for 1983 and 1987;
PP_{83}, PP_{87} = purchase price for 1983 and 1987, £.

The accuracy of the projection over four years which was confirmed by reference to a recent tractor price guide (Anon, 1987) is also

Table 3.2 Ten year price indices for various categories of farm equipment

Year	Annual price indices; 1980 = 100		
	Tractors	All agricultural machinery	Soil preparation and cultivation machinery
1978	80.6	77.1	80.5
1979	89.4	88.3	88.5
1980	100.0	100.0	100.0
1981	108.5	104.9	101.8
1982	114.8	111.9	106.3
1983	124.9	114.2	110.3
1984	134.1	119.1	115.3
1985	143.8	126.5	121.0
1986	150.8	134.5	129.8
1987	151.2	140.4	135.5

significant for the appraisal of the decremental depreciation technique. A sample of the pro-forma output is shown in Table 3.3 for a set of input data which includes the standard values of the repair and resale coefficients. The ownership period was taken as 10 years and the annual use 1000 hours. The repair costs increase with the age of the machine by levying an increasing percentage of the purchase price, whilst the insurance charges decline with machine age by applying a fixed percentage to the written-down value. As the salvage value at the end of the tenth year is more than the written-down value, there is a balancing charge for tax adjustment. The equal annual mortgage repayments have a declining interest component eligible for tax relief. In addition to the present annual cost, fuel, labour and shelter are also listed in current values but were not included in the financial comparisons as their present annual costs are constant. (Appendices A2, A3).

The annual ownership costs for ownership periods from 1 to 10 years are shown in Figure 3.2. These costs rapidly decline as the ownership period is extended to 3 years but, thereafter, the annual cost curve flattens out. The annual ownership cost for <u>each</u> year of a two year ownership is £3145 compared with £2702 for <u>each</u> year of a seven year ownership period. The minimum point on the annual cost curve is located at its intersection with the marginal holding cost curve for an ownership period of 7 years. Table 3.4 shows the calculation of the annual ownership and the marginal holding costs.

Ideally, machines should be replaced before their age exceeds the period of ownership for which the annual cost is a minimum. The extra costs of not doing so can be obtained by summing the differences between the marginal cost curve and the annual cost curve

Table 3.3 Standard input data with a sample of the pro-forma output of annual ownership costs

Input data for 2WD tractor

Purchase price	= £16000			Annual use, h	= 1000		
Loan rate	= 0.113	Interest rate	= 0.0815	Inflation rate	= 0.05	Tax rate	= 0.27
Fuel cost £/l	= 0.14	Labour cost £/h	= 5.00	Shelter	= 0.01		
Repair coefficients:	RA = 0.012	RB	= 2.0				
Resale coefficients:	k1 = 0.237	k2	= 0.005				

Output cost data for 2WD tractor

Age Yr	Inflation factor	Investment factor	Repair cost £	Insurance £	Actual repair & insurance £	Actual capital allowance £	Actual interest charge £	Total tax allowance £	Actual cash outgoing £	Discount cash flow £	Inflated discount factor
1	1.050	1.082	192	177	387	4000	1808	6195	1465	1355	0.971
2	1.102	1.170	576	146	796	3000	1701	5497	2063	1764	0.943
3	1.158	1.265	960	122	1253	2250	1583	5085	2631	2080	0.915
4	1.216	1.368	1344	104	1760	1688	1451	4898	3188	2330	0.888
5	1.276	1.480	1728	89	2319	1266	1304	4889	3750	2535	0.863
6	1.340	1.600	2112	78	2935	949	1140	5025	4329	2706	0.837
7	1.407	1.731	2496	68	3608	712	958	5279	4934	2851	0.813
8	1.477	1.872	2880	60	4343	539	755	5633	5573	2978	0.789
9	1.551	2.042	3264	53	5143	400	530	6076	6256	3091	0.766
10	1.629	2.189	3648	47	6019	300	279	3483	3813	1742	0.744
										£23431 /	8.53

Actual salvage value = £4017
Mortgage payment = £2751
Actual balancing charge= £3116

	Present annual cost	= £2747
excluding	(Fuel cost	= £2541
tax	(Labour cost	= £5000
allowances	(Shelter cost	= £ 160

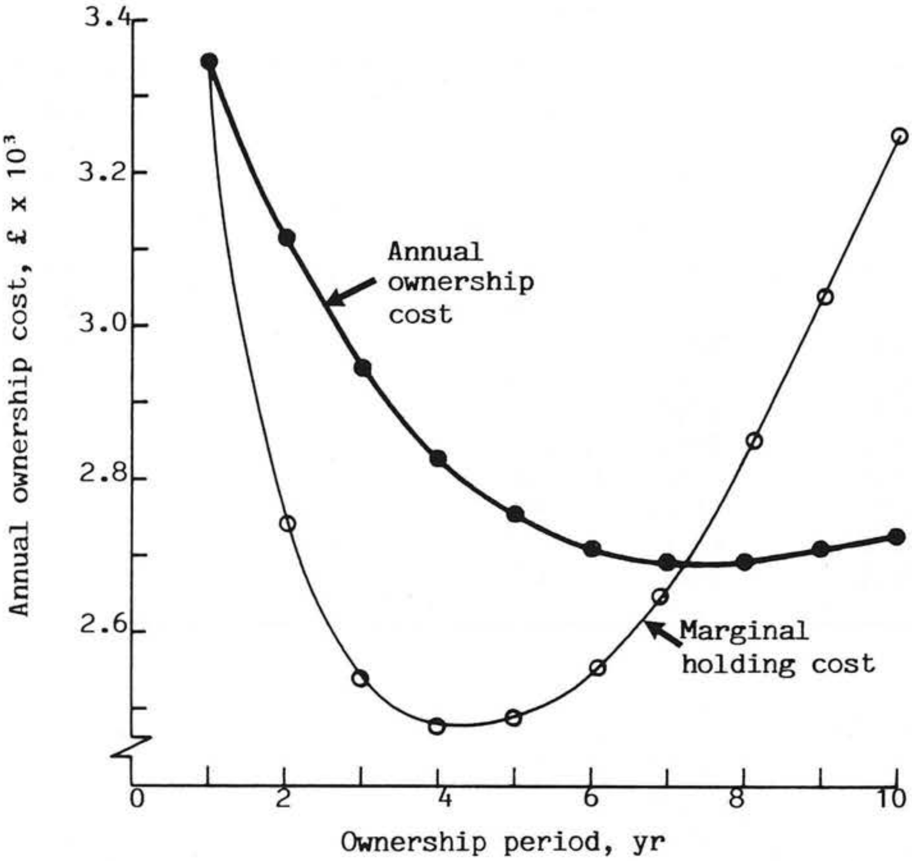

Fig 3.2 The optimum period of machine ownership is when the marginal holding cost is equal to the annual ownership cost using discounted cash flows

Table 3.4 Calculation of annual ownership and marginal holding costs at 27% tax

Age yr	Actual repair and insurance £	Deprec-iation £	Actual interest charge £	Marginal holding cost £	Annual cost £
1	387	2679	1808	3388	3388
2	796	2119	952	2766	3145
3	1253	1687	668	2557	2972
4	1760	1352	527	2478	2850
5	2319	1089	443	2488	2770
6	2935	883	387	2555	2723
7	3608	717	348	2680	2702
8	4343	587	319	2835	2701
9	5145	479	297	3020	2717
10	6019	392	279	3223	2747

for each year of additional ownership. There are also the penalties of untimely operations which may accrue through poorer reliability of an older machine.

3.2 Tractor plough model

The development of a machinery selection programme was simplified by analysing the tractor-implement performance and matching the tractor and implement combinations for tillage operations (Appendix B). The programme is built to select a single tractor matching with different size of plough depending on the draught, and the speed of each selected gear of the tractor utilised during the operation. For each acceptable combination of tractor and plough determined, the costing routine is used to calculate the annual costs.

3.2.1 Matching tractor-plough combinations

The selection of tractor-plough combination is mainly based on prediction of soil characteristics such as strength, workability and moisture prediction of plough draught and tractor power. Other factors affecting tractor performance are the load on the tractor and the weight transfer.

Based on Dwyer's work (1984), the Edinburgh Tractor Performance Model has been extended by substitution of some input data such as: minimum, maximum and incremental values of the tractor speed for ploughing to the number of gears and speed in each gear. The engine torque and speed at the maximum power have been added to characterise a tractor. This information can be found in an official test report or the manufacturer's specification for any tractor. The gear ratio which is the engine speed divided by the wheel speed, and the engine torque available at the driving wheels are calculated to complete the performance analysis of the tractor. This additional calculation eliminates the weight/power ratio as a constraint by forcing the ratio value to be less than the limit (Fig 3.3). A number of filters are used to select the appropriate and realistic tractor/implement combinations such as:

1. the pull produced by the tractor should be either equal to or exceed the sum of the plough draught and the rolling resistance of the undriven wheels of the tractor;
2. the tractor pull should not be greater than 1.25 of the plough draught to avoid a very powerful tractor and low draught implement;
3. the tractive efficiency of the tractor should not be less than the acceptable level of 0.65;
4. the engine torque in any selected gear should not reach the maximum.

The power level varied according to the engine parameters (torque and speed at maximum) and a given recommended load/tyre dimension. A series of load/tyre dimensions and their corresponding engine parameters are available to match the draught at medium plough cut depth of 0.25 m for various sizes of fully mounted ploughs (2 to 8 furrows) with various gear speeds. In each optimisation, width, speed of gear, load/tyre dimensions, and engine characteristics were given to select the optimum power level matching the implement width and the draught required. Table 3.5 contains full details of the selected combinations of tractor and plough consisting mainly of: different gears of a tractor in the top of each column and the tractor, plough and soil specifications. From these resources, a series of three two-wheel drive tractors have been selected as a random sample

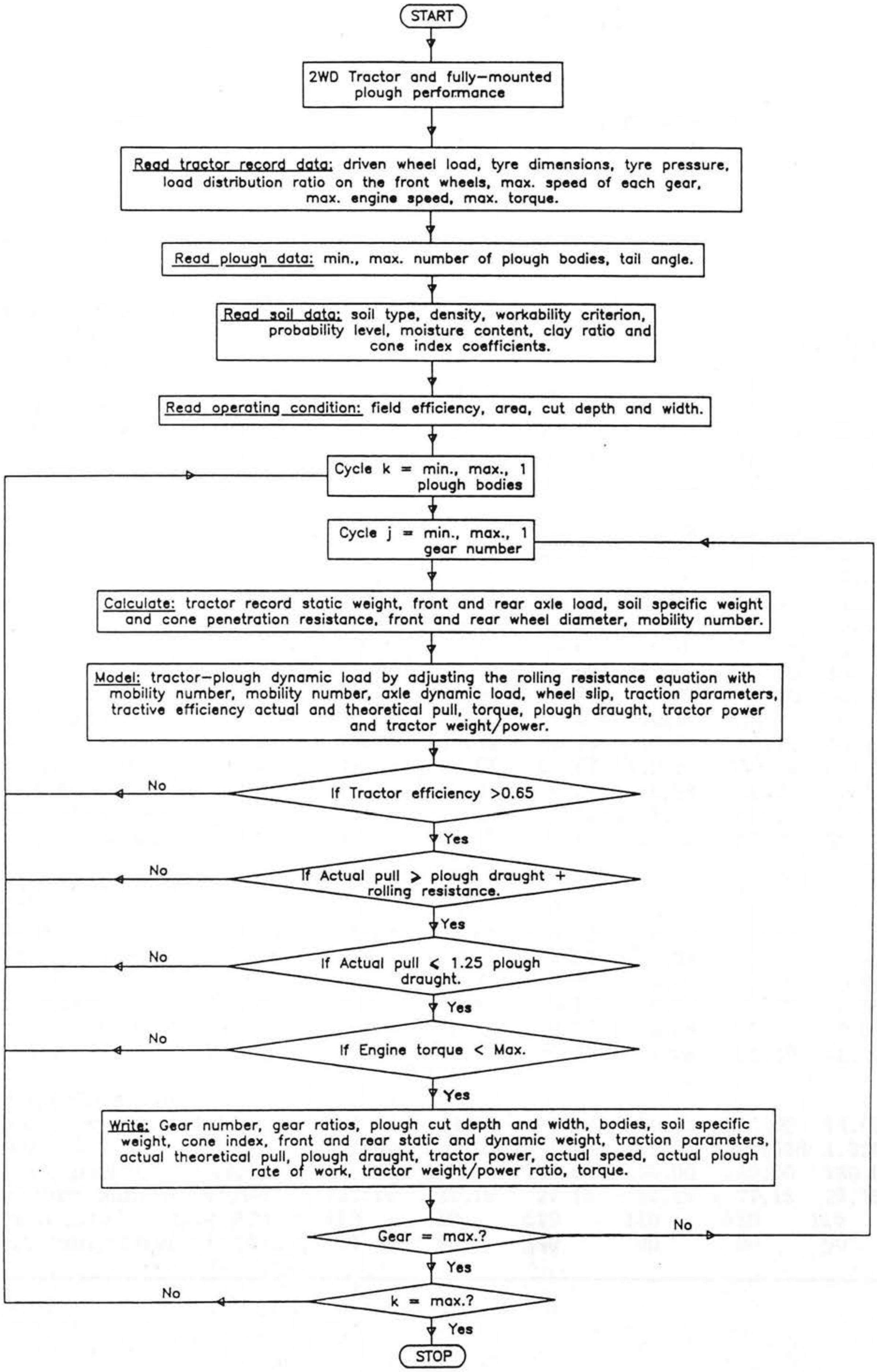

Fig 3.3 Flow chart for a single two-wheel drive tractor and fully mounted plough combination

Table 3.5 Tractor-plough combination for different gears at 80% field capacity

Gear number :	1	2	3	4	5	6
Tractor specification:						
gear ratio	253.35	179.85	126.40	87.63	77.08	63.41
max power required (kW)	45	45	45	45	45	45
PTO power (kW)	11.19	15.76	22.04	31.79	36.14	43.93
drawbar power (kW)	8.02	11.30	15.82	22.82	25.94	31.54
static weight (kN)	46.93	46.93	43.38	48.38	48.38	48.38
dynamic weight (kN)	52.81	52.81	52.81	52.81	52.81	52.81
weight/power (kg/kW)	82.93	82.93	81.88	81.88	81.88	81.88
dynamic axle load						
front (kN)	15.61	15.61	16.09	16.09	16.09	16.09
rear (kN)	37.19	37.91	36.72	36.72	36.72	36.72
front tyre dimension(in)	7.5	7.5	7.5	7.5	7.5	7.5
	18.5	18.5	18.5	18.5	18.5	18.5
rear tyre dimension (in)	16.9	16.9	16.9	16.9	16.9	16.9
	30.0	30.0	30.0	30.0	30.0	30.0
front tyre pressure(kPa)	120.00	120.00	120.00	120.00	120.00	120.0
rear tyre pressure (kPa)	80.00	80.00	80.00	80.00	80.00	80.00
wheel slip (%)	10.13	10.13	10.11	10.11	10.11	10.11
actual thrust (kN)	13.98	13.98	13.74	13.74	13.74	13.74
engine torque (Na)	48.99	69.01	96.97	139.88	159.02	193.0
front rolling res (kN)	0.61	0.61	0.64	0.64	0.64	0.64
rear rolling res (kN)	1.23	1.23	1.21	1.21	1.21	1.21
maximum thrust (kN)	27.57	27.57	27.25	27.25	27.25	27.25
Plough specification:						
bodies	4	4	3	3	3	3
weight (kN)	5.88	5.88	4.43	4.43	4.43	4.43
forward speed (km/h)	2.07	2.91	4.14	5.98	6.80	8.26
cut depth (m)	0.20	0.20	0.20	0.20	0.20	0.20
cut width (m)	0.25	0.25	0.25	0.25	0.25	0.25
actual work rate (ha/h)	0.17	0.23	0.25	0.36	0.41	0.50
draught (kN)	13.53	13.70	10.53	11.09	11.40	12.05
Soil specification:						
specific weight (kN/m^3)	14.02	14.02	14.02	14.02	14.02	14.02
cone index (kN/m^2)	1.336	1.336	1.336	1.336	1.336	1.336
field capacity (mm)	130.00	130.00	130.00	130.00	130.00	130.0
moisture content (%w/w)	27.15	27.15	27.15	27.15	27.15	27.15
workability (% of FC)	110	110	110	110	110	110
probability level (%)	90	90	90	90	90	90

to calculate the cost per hectare to plough an area of 100 ha. The two-wheel drive tractors selected are: 45 PTO kW, 61 PTO kW, and 74 PTO kW. It is assumed that the fuel price is £0.14/litre and labour is available as required at a rate of £5/hour.

For simplicity of the model, the number of working days is a full week including holidays. The assumption of 8 hours/day is taken for field work for any sequence of farm operations.

3.2.2 **Tractor plough optimisation**

Optimisation does not only match different sizes of machine to the appropriate tractor power level, but also identifies the cost which is the most important part. This involves a knowledge of the marginal price change for different sizes of utilised machines.

Thus, it can be seen that the annual cost of a machine depends on its size and hours used for a farm operation. This is due to the tractor-implement performance and their work rate to cover an area. It is assumed that the annual tractor hours are those spent on ploughing the area of 100 ha, plus a certain number of hours utilised for other operations of the year. The ploughing period depends on the rate of work which is related to the tractor speed and the implement size to cover a given area. Four small or medium tractors take a longer period to complete a job than a big tractor. In general terms, ploughing a hectare takes 16 hours with a 30 PTO kW tractor, 12 hours with a 45 PTO kW, 10 hours with 60 PTO kW and 8 hours with a 75 PTO kW. Therefore, the amount of hours added to the ploughing hours could not be the same, since the operating time depends on the rate of work of a given size of equipment. From this procedure, an interesting point emerges in that the faster the speed of operation, the less machine hours used and so the lower the accumulated repair costs. The introduction of a speed factor compensates for the extra repair costs to the implement incurred by high speed operation.

3.3 Sensitivity analysis of resale and repair costs

Sensitivity analysis was used to explore the effect of inadequacies in the evaluation of resale data on the credibility of the costing procedure and the viability of the replacement policy. The sensitivity of present annual ownership costs to changes in repair costs and in tax rates was also examined. The range of values included in the sensitivity analysis is given in Table 3.6, standard input values being adopted for all variables other than those under scrutiny. The only exception to this procedure was for the investigation of the effects of inflation in the absence of taxation on present annual costs; the loan interest rate was assumed equal to the investment interest rate so that the total present value of the mortgage became the same as the purchase price.

3.3.1 Variation in resale value

Four depreciation curves are illustrated in Figure 3.4, the standard logarithmic equation which does not fit the British data, the 'best fit' logarithmic equation, and the 'best fit' first order and second order decremental equations. The resultant annual cost curves are shown in Figure 3.4.

For logarithmic depreciation, the resale to purchase price ratio close to the time of purchase is entirely dependent on the value of the first year correction factor, SA. There is an immediate loss of value of 32 per cent and 20 per cent, increasing to more than a third and a

Table 3.6 Range of values of the variables in the sensitivity analysis

Variable	Values of the input data		
		Standard	
First year correction factor, SA	0.8	-	0.68
Annual depreciation factor, SB	0.85	-	0.92
Resale exponent, k_1	0.20	0.24	-
Resale exponent, k_2	0	0.005	-
Repair constant, RA	0.008	0.012	0.01
Repair exponent, RB	1.9	2.0	2.1
Annual use, h	750	1000	1250
Tax rate	0	0.27	0.40
Inflation rate	0	0.05	0.10
Investment interest rate	0.03	0.0815	0.133
Loan interest rate	0.06	0.113	0.166

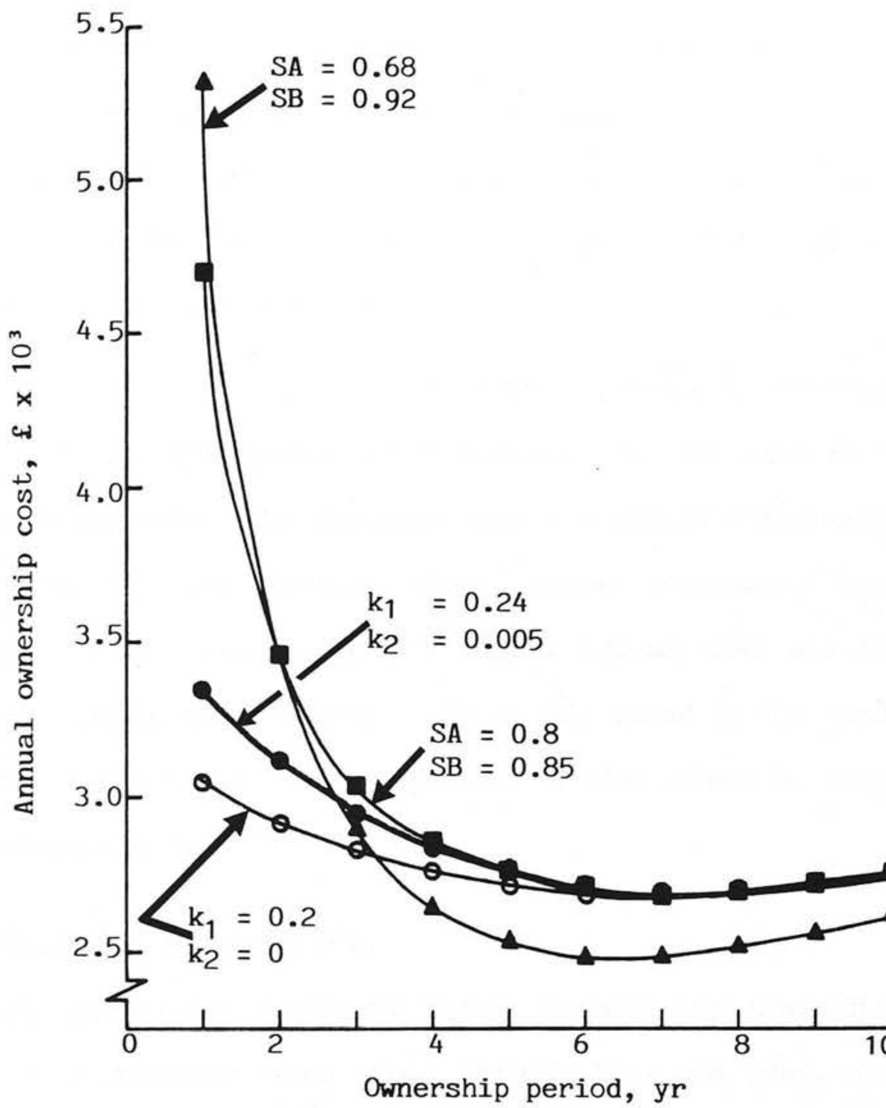

Fig 3.4 Annual ownership costs for different levels of depreciation, the heavy line representing the most accurate prediction of resale value by decremental depreciation

quarter of the initial purchase price at the end of the first year for the standard and 'best fit' equations, respectively. After this initial drop, the annual depreciation factor governs the annual loss in value. Thus, a high value of the first year correction factor and a low value of the annual depreciation factor both over-estimate depreciation of nearly new machines. This results in excessively high annual costs for one and two year periods of ownership. Although the error declines as the period of ownership is extended, a high initial depreciation can lead to a steadily declining annual cost curve and a totally misleading replacement policy.

The annual cost curves for decremental depreciation present a less dramatic variation with period of ownership. As the value of the first order resale exponent becomes more negative and is compensated by a larger value for the second order resale exponent, the initial depreciation is increased to give a higher annual cost and to extend the optimum replacement period. Whilst this trend is the same as for logarithmic depreciation, the magnitude of the effect is smaller and within realistic limits.

3.3.2 **Variation in repair cost**

Repair and maintenance costs are highly variable and unpredictable as to time of occurrence and, even though they do show consistent trends in relation to accumulated use, a standard variation equal to the mean is a typical variation in these data (ASAE, 1986). The magnitude of the logarithmic repair function (eqn 2.58) is governed by the values of the repair constant and the repair exponent. The repair constant, RA, causes a proportional change in the accumulated repair and maintenance cost for each and every year throughout the life of the machine. The repair exponent, RB, controls the distribution of the repair costs over the life of the machine, a higher value of the repair exponent shifting a greater proportion of the costs onto older machinery. The standard values of 0.012 for the repair constant and 2.0 for the repair exponent for two-wheel drive tractors are used to demonstrate the relative effect of varying these two coefficients (Fig 3.5). For a tractor life of 10000 hours, the total accumulated repair cost is 120 per cent of the purchase price using the standard repair coefficients, whereas the lowest curve gives 80 per cent and the highest curve gives 160 per cent.

Varying the level of the repair costs alters the replacement period (Fig 3.6). For example, increasing the value of the repair constant from 0.008 to 0.012 and to 0.016 brings forward the minimum annual cost point from a ten year period of ownership to seven and five years, respectively.

3.3.3 Variation in annual use

The level of annual use has a substantial effect on repair costs and on the annual ownership cost curves (Fig 3.7). For an annual use of 750 hours, the minimum annual ownership cost is only two thirds of that for an annual use of 1250 hours and the optimum replacement age alters from twelve to five years (Table 3.7). As the optimum replacement age falls, there is also a shorter decision-making period over which the annual ownership costs deviate less than 5 per cent above the minimum.

3.3.4 Variation in tax rate

The effect of three tax rates (0, 27 and 40 per cent) on the level of annual ownership costs is shown in Figure 3.8. The annual costs fall

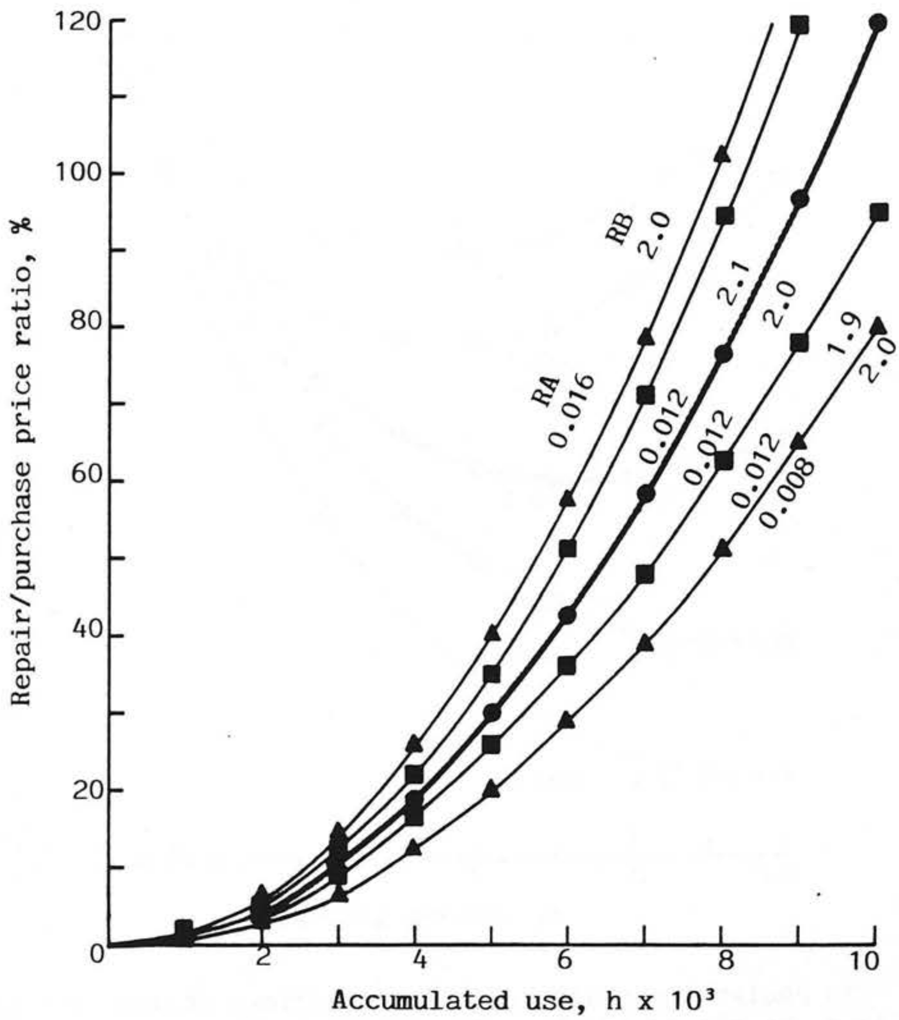

Fig 3.5 Repair/purchase price percentages for different values of the repair constant, RA, and the repair exponent, RB, the heavy line representing the repair costs for two-wheel drive tractors

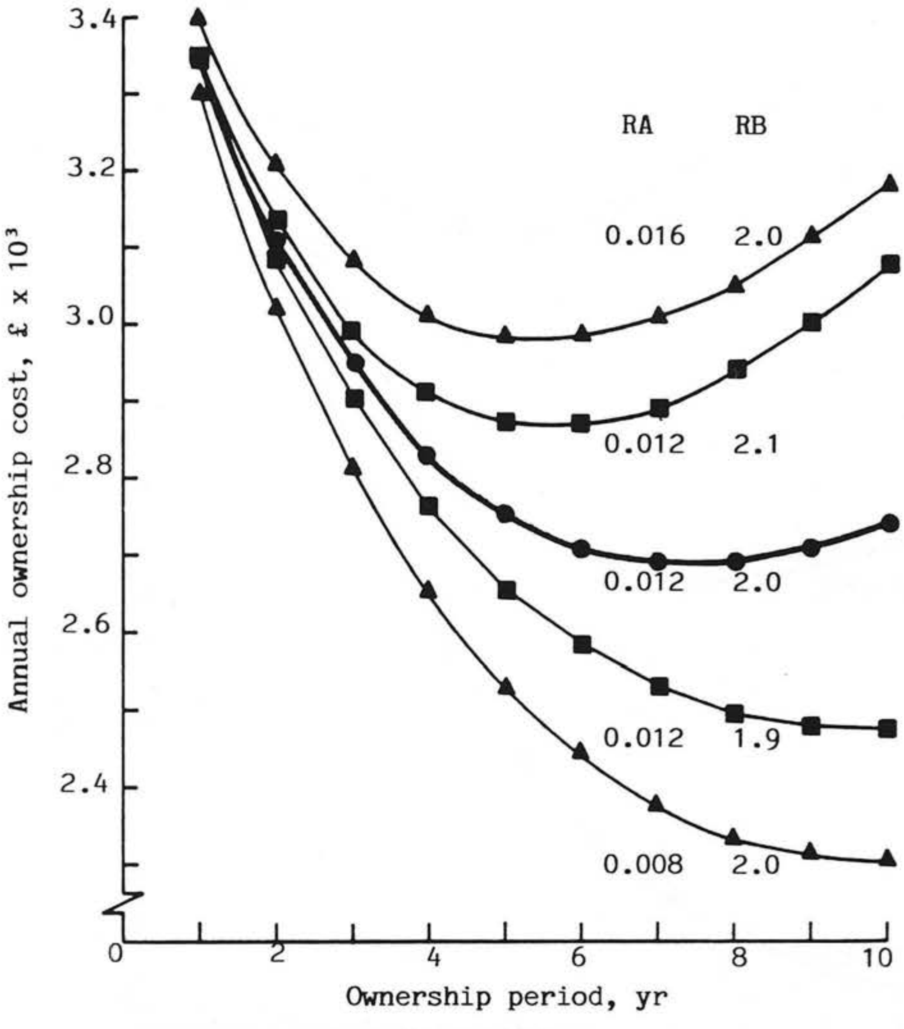

Fig 3.6 Annual ownership costs for different values of the repair constant, RA, and the repair exponent, RB, the central curve being based on the standard repair costs for two-wheel drive tractors

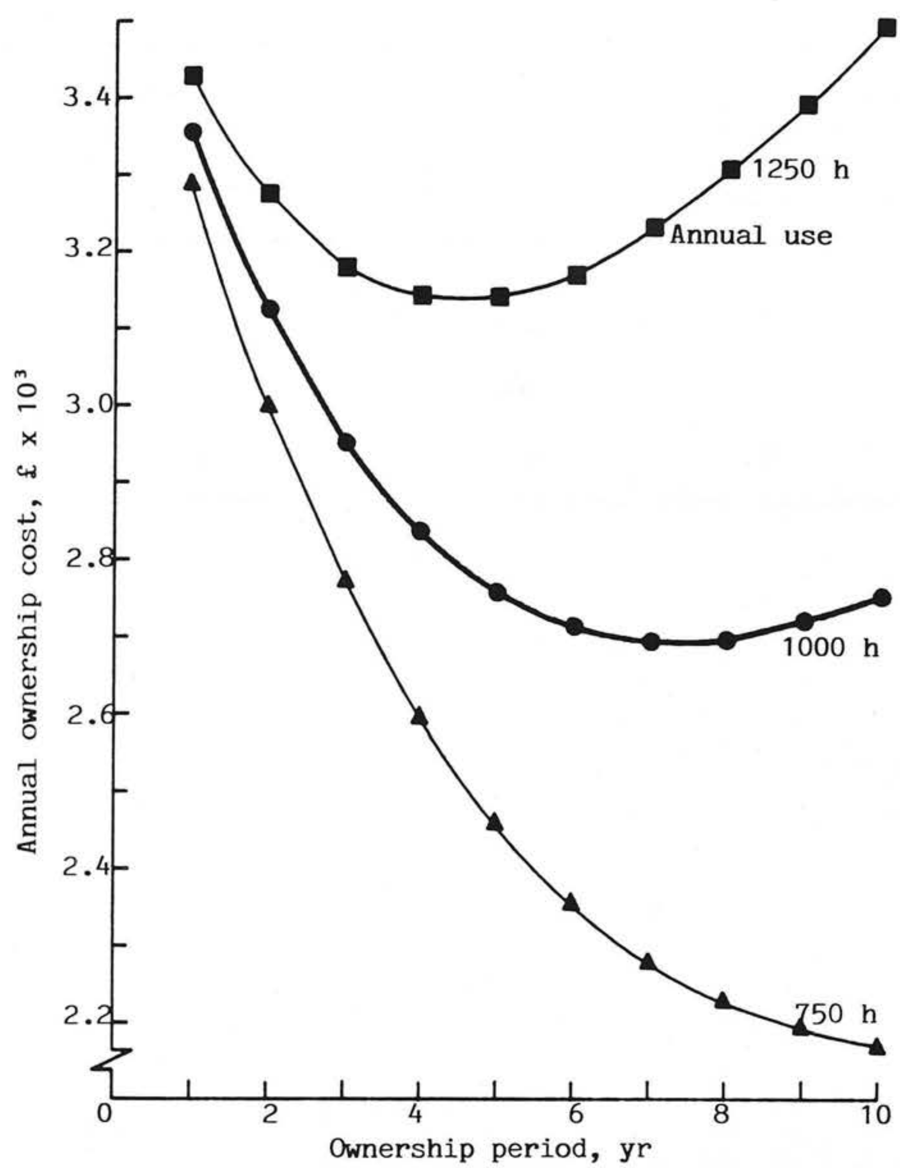

Fig 3.7 The effect of annual use on the annual ownership costs for a two-wheel drive tractor

Table 3.7 The effect of annual use on the optimum replacement age of two-wheel drive tractors and the duration of the replacement decision-making period when annual costs deviate less than 5 and 10 per cent above the minimum

Annual use, h	Optimum replacement age, yr	Minimum cost, £	Period over which costs deviate less than 5% from minimum, yr	Period over which costs deviate less than 10% from minimum, yr
750	12	2145	5	6
1000	8	2701	4	5
1250	5	3155	3	4

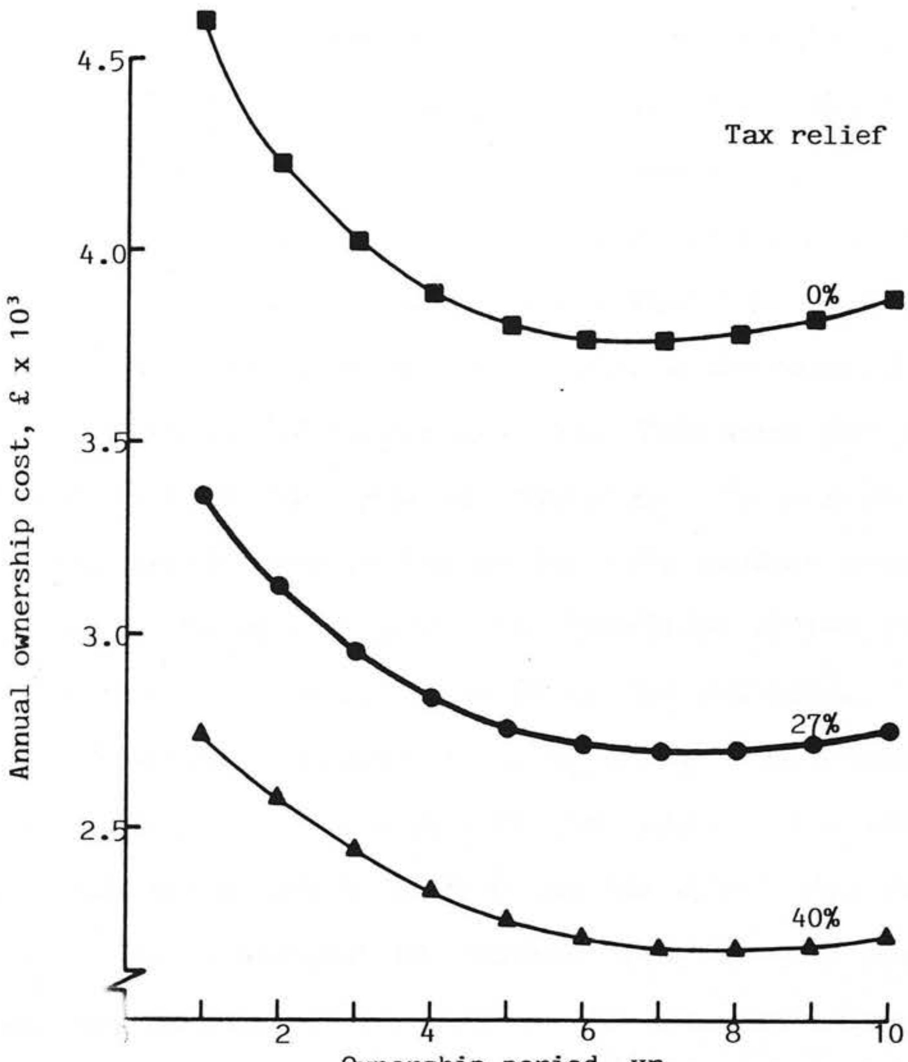

Fig 3.8 The effect of tax relief on the annual ownership costs of two-wheel drive tractors

in proportion to the tax liability and this encourages earlier machine replacement, even though the minimum costs relate to similar periods of ownership.

In reality, costing procedure cannot be applied for a single and isolated machine. Costing is considered as an item linking new and old machines, saving of one could increase the balance of another. In fact, these savings and costings are not happening concurrently but separated by years at a time. The point is that tax relief is not refunded in the current year but is paid a year later. If this procedure is applied for a single machine on its own for a normal replacement, the problem becomes more complex than that used in the current study. One extra year has to be added in the calculation of the annual cost at the end of ownership (N+1). This extra year holds the tax refund from the last year of ownership. To compare this method with the method used in this project (one machine assuming the tax is paid in the current year), the calculation of two to ten years was used as an exercise to determine the difference. The annual cost is considerably smaller at the beginning. An example is given in Table 3.8 of a machine held for two years. The present annual cost, with tax at 27% is £3146 if the tax is refunded in the current year. The calculations are repeated with the same machine life but the tax deferred (Table 3.9). The tax relief from the previous machine is not shown in year 1; the tax relief in year 3 is deducted from the balance to give a low present annual value or could be considered as year 2 tax relief for the next machine replacement in the fleet. In this case, the annual cost is £2230 compared with £3146 with the previous method. The annual cost increases progressively each year until the end of ownership. At year 10, it reaches £3443

Table 3.8 An output pro-forma of two years of ownership with tax paid in current year

Purchase price (£)	=	16000.00			Used hours (h/yr)	=	1000.00
Loan rate	=	0.1130	Interest rate	= 0.0815	Inflation rate	=	0.0500
Fuel cost (£/l)	=	0.14	Labour cost (£/h)	= 5.00	Shelter	=	0.01
Repair coefficients: Ar	=	0.012	Br	= 2.000			
As	=	68.000	Bs	= 0.920			
k1	=	0.237	k2	= 0.005			

Output cost date : TR

Age	Inflation factor	Investment factor	Repair cost	Insurance	Actual repair & insurance	Actual capital allowance	Actual interest charge	Total tax allowance	Total tax relief	Actual cash outgoing	Discount cash flow	Inflated discount factor
Yr		£	£	£	£	£	£	£	£	£	£	%
1	1.050	1.082	192.00	176.50	386.93	4000.00	1808.00	6194.92	1672.63	8094.46	7484.48	0.971
2	1.102	1.170	576.00	146.03	796.04	3000.00	952.34	2545.52	687.29	-1713.94	-1465.36	0.943

Actual salvage value	(£) =	11202.86
Mortgage payment	(£) =	9380.17
Balancing charge	(£) =	2202.86

6019.12 / 1.913

Present annual cost	(£) =	3145.66
Fuel cost	(£) =	2540.69
Labour cost	(£) =	5000.00
Shelter cost	(£) =	160.00

Table 3.9 An output pro-forma of two years of ownership with tax deferred

Purchase price (£)	=	16000.00				Used hours (h/yr)	= 1000.00
Loan rate	=	0.1130	Interest rate		= 0.0815	Inflation rate	= 0.0500
Fuel cost (£/l)	=	0.14	Labour cost (£/h)		= 5.00	Shelter	= 0.01
Repair coefficients: Ar	=	0.012		Br	= 2.000		
As	=	68.000		Bs	= 0.920		
k1	=	0.237		k2	= 0.005		

Output cost date : TR

Age Yr	Infla-tion factor	Invest-ment factor £	Repair cost £	Insur-ance £	Actual repair & insurance £	Actual capital allowance £	Actual interest charge £	Total tax allowance £	Total tax relief £	Actual cash out-going £	Discount cash flow £	Infla-ted discount factor %
1	1.050	1.082	192.00	176.50	386.93	4000.00	1808.00	6194.92	-	9767.10	9483.85	0.971
2	1.102	1.170	576.00	146.03	796.04	3000.00	952.34	2545.52	1672.65	-2699.28	-2545.42	0.943
3			-	-	-	-	-	-	687.29	-687.29	-628.87	0.915

Actual salvage value (£) = 11202.86
Mortgage payment (£) = 9380.17
Balancing charge (£) = 2202.86

6309.56 / 2.829

Present annual cost (£) = 2230.31
Fuel cost (£) = 2540.69
Labour cost (£) = 5000.00
Shelter cost (£) = 160.00

without having any optimum point for replacement (Table 3.10).

3.3.5 Variation in inflation rate

When the real investment interest rate is held constant at different levels of inflation, the annual ownership costs are unaffected in the absence of any tax liability assuming that the loan interest rate is the same as the investment interest rate. Tax liability and higher loan rates do cause minor changes to the annual ownership costs but the variation is only of the order of $\pm 2\%$ for the range of input data under investigation.

3.4 Least cost tillage

Tractor and implement width are considered as a combined system to obtain different parameters such as rate of work, draught and drawbar power. To draw the drawbar power curves of 10 kW, 20 kW, 30 kW and 40 kW for a depth of 20 or 25 cm as shown in Figures 3.9 and 3.10, the draught equation 2.6 is used by maintaining a given drawbar power value constant on one side of the equation, varying sequentially the number of ploughs from the minimum to the maximum (2-8 bodies), and correcting at the same time the squared velocity value to balance the equation. The exercise is repeated to complete all the drawbar power curves. The same scenario has been adapted to represent the rate of work of 0.25 ha/h, 0.50 ha/h and 0.75 ha/h, by using the rate of work equation which is equal to the product of the speed, width of bodies, number of bodies and the field efficiency. The variation of the width of work influences the speed value to yield the given rate of work. High width corresponds to a low speed to coordinate the curve value and vice versa.

The calculation of tractor-implement costs per hectare to plough an

Table 3.10 Annual cost with tax refund next year

Year	Annual cost £
1	1825
2	2230
3	2437
4	2560
5	2680
6	2806
7	2942
8	3093
9	3374
10	3443

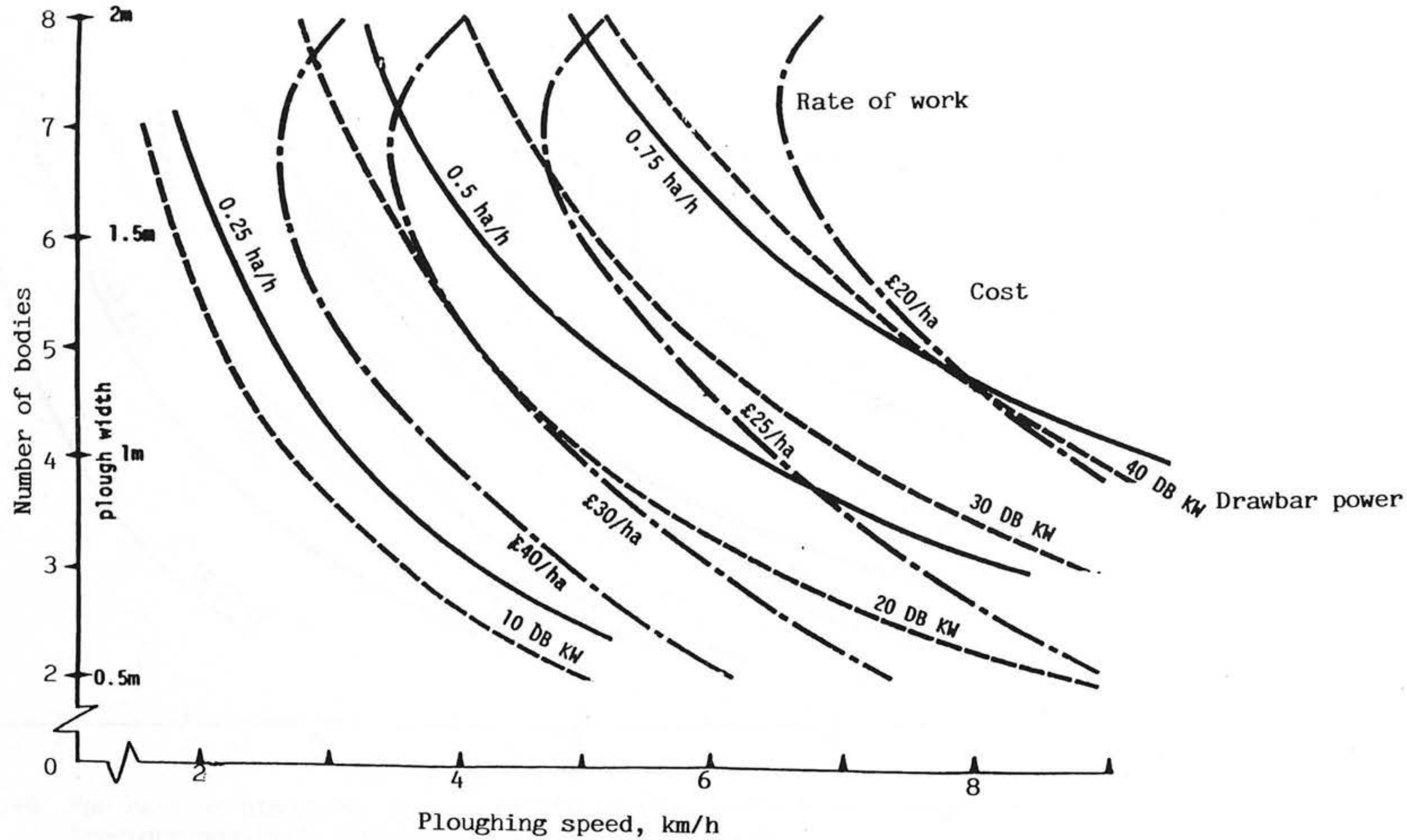

Fig 3.9 The cost of ploughing an area of 100 ha with various two-wheel drive tractors and fully mounted ploughs at 0.20 m depth

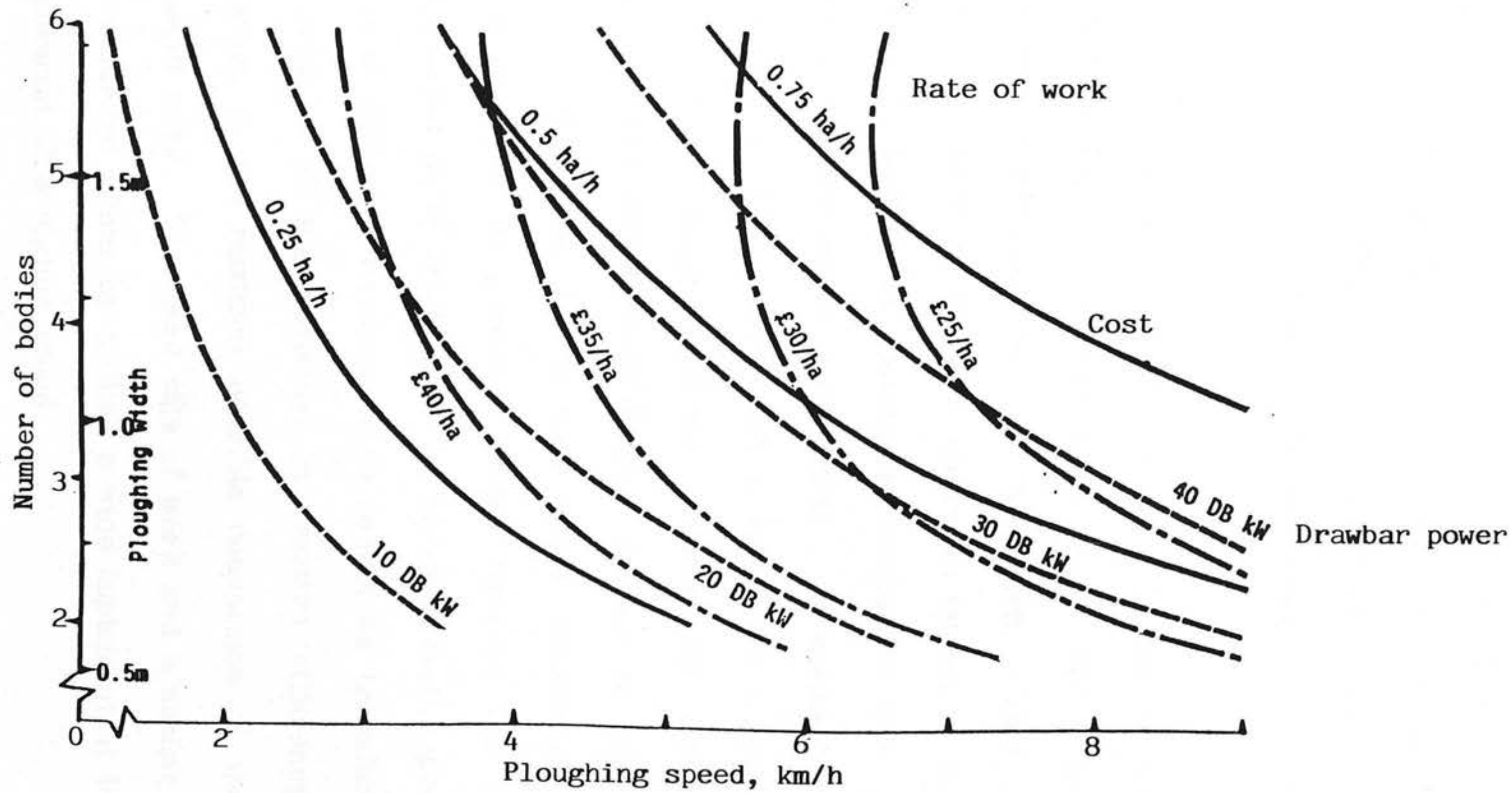

Fig 3.10 The cost of ploughing an area of 100 ha with various two wheel-drive tractors and fully mounted ploughs at 0.25 m depth

area of 100 ha with a series of various sizes of two-wheel drive tractors (45 PTO kW; 61 PTO kW and 74 PTO kW) at different depths respectively 0.20 m and 0.25 m are plotted on the same width and speed coordinate system as the rate of work and drawbar power curves. The cost calculations depend on the annual use of the tractor and the rate of work. A small tractor of 45 PTO kW can manage a 3 or 4 furrow plough at 20 cm depth, but it can only pull a 2 furrow plough at 25 cm depth and at a different speed. It is very convenient to choose an optimum point according to the width and speed used.

An extra two-wheel drive of 94 PTO kW which can manage 7 or 8 furrows at 0.20 m depth with acceptable speed was added to the series of tractors to continue the cost calculation. This calculation was to confirm the shape of the cost curve as shown in Figure 3.9. It is not realistic to pursue the costing calculation for more than an 8 furrow plough as a fully mounted implement. It would be advisable and more practical to hitch more than 6 bodies as a semi-mounted plough to an extra large powered tractor by matching the corresponding dynamic weight coefficient. It may be reasonable to contour the costing curves, but it does create discontinuity of the curve through changes in purchase prices between the two-wheel drive and four-wheel drive tractors. The power curves represent the drawbar power of different tractors which cannot be transformed into PTO power because of the variation in tractive efficiency. The tractive efficiency is the maximum possible conversion of the engine power into useful work. The same rate of work and a similar drawbar power can be achieved either by pulling a wide implement at low speed or narrow implement at a higher speed.

The ploughing cost curves against speed and width, using different two-wheel drive tractor power to complete the same job, follow the drawbar power and the rate of work curves until a certain width of an implement, then start to deviate markedly because of the extra power required. When a large powered tractor is matched to a wide implement (8 furrows) to develop an efficient high drawbar power, the rate of work is increased and less time is required. Hence the hourly cost of the tractor increases with a smaller proportion of annual use for ploughing, depending on the tractor purchase price.

However, the cost per hectare drops because of the high rate of work. Of course, labour and fuel costs decrease as the tractor is used efficiently with bigger machines at the right speed to complete the job.

A sensitivity analysis was used to investigate the effect of the depth of ploughing on the cost per hectare, by increasing it from 0.20 m to 0.25 m and the width of the furrow respectively from 0.25 m to 0.30 m. The same draught value could be held in both cases by either keeping a constant value of width and decreasing speed or keeping the speed value constant and decreasing the width of ploughing by reduction of the number of bodies. Therefore, the rate of work declines and the plough period increases as more time is required to finish the job, so the fuel and labour costs increase with the proportion of annual use and the total cost per hectare increases.

4. WHOLE FARM MACHINERY MANAGEMENT

4.1 Linear programming model

Linear programming is a mathematical technique which has been developed over the last thirty years to deal with complex planning and investment problems. Restricted resources are allocated by linear programming to maximise or minimise some chosen objective. In agriculture, linear programming can be applied to allocate resources to alternative enterprises, make decisions on planning different sequences of operations, and determine a farm's labour and machinery needs. Linear programming problems are based on four main steps:

1. identification of the problem to be solved (formulation) and collection of the necessary data and information;
2. conversion of the problem into a matrix form;
3. solution of the problem through the application of linear programming rules and procedures;
4. interpretation of the results obtained from the solutions.

The scheduling model described in this study comprises three programs named: LP80P1; INTEGER; and LP87PR. (Appendices C1, C2, C3).

4.1.1 The matrix and its limitations

Linear programming packages require the data file to be of a particular form (matrix form). A computer program LP80P1 is usually written to read the code and generate the data file from the raw data. In this situation, the raw data file required has been named "FARM" which is an input data file for the LP80P1 program (Appendix C1). After the formulation of the problem (goal) which depends on the farmer's or manager's decision on the crops to be produced in the current year, a farm planning matrix was built for a typical cereals and root crop farm in East Scotland for a certain area on a soil of the Macmerry series. Possible cropping activities included in the rotation are: winter barley, spring barley, winter wheat, and potatoes as a root crop for the current year.

The objective function sought initially to minimise the annual machinery costs subject to:

- depreciation costs of any selected machine or item of equipment;
- land constraints (area in hectares);
- time constraints (time in hours);
- labour constraints.

The matrix comprised (m_c) cropping and harvesting activities and (n_c) constraints to plan the harvesting and establishment operations, depending on the rotation applied, without ignoring transport activities which play an important role in farm power scheduling. The area available in any farm plan is the most obvious constraint. To build the matrix for the planning problem, the most vital consideration is to formulate the rotation of the crops grown, and to identify adequately their relationship. The rotation considered in this study is potatoes, winter wheat, spring barley and winter barley for two years, then returning to potatoes, each crop representing one fifth of the total area. The sequence of crops where the area of one crop depends on the area of the previous crop determines the feasibility of the crop rotation. Each crop requires land preparation, planting, harvesting and transport activities. The description of the matrix starts with the total area available for the year, followed by the rotational constraints for different crops used in the rotation to limit their area in relation to the total area, the definition of the activities, the number of hours supplied and the number of hours required by each activity within a period, followed by the constraints for each machine and implement, the last row of the matrix is the objective function which determines the cost. Figure 4.1 shows an example of a matrix with different activities for one crop in the rotation. The activities are: harvesting and transport, ploughing, cultivating and drilling in one period. To reduce the size of the matrix, one size of tractor with the matched implement necessary to perform the job and one combine harvester size are considered in the example. The matrix could be extended by considering the four crops of the rotation with all the necessary activities in different periods of the year and with different sizes of tractors and machinery. The input data required is a summary of the information about activities in different periods of the year, starting with harvesting of the earliest ripening crop (winter barley). Each operation would determine whether the selected machinery is sufficient to satisfy work day constraints at a given level of probability. The information which a farmer or a manager needs to know is:

- time needed to produce a crop;
- a set or sets of equipment to perform operations for the crop rotation;
- workable time available for different operations for each crop (year).

Calendar date constraints for each field operation, and suitable field work days are required to calculate available field time. Rainfall, temperature, soil type and soil condition combine together to determine whether or not a day is available for work of a particular type. Work days were specified from soil moisture data during the establishment

		Crops				Coefficients				Activities						Machinery							
		Potato	W. Wheat	S. Barley	W. Barley	Harvesting	Ploughing	Cultivating	Drilling	Harvest	Transport	Transport	Plough	Cultivate	Drill	C. Harvester	Trailer	Trailer	Plough	Cultivator	Drill	Relation	Supply
Land		−1	−1	−1	−1																	≤	−200
Rotational constraints	W. Wheat	1	−1																			≤	0
	S. Barley		1	−1																		≤	0
	W. Barley			1	−0.5																	≤	0
	Potato	−1			0.5																	≤	0
Activities definition	Harvest				1	−1.3																≤	0
	Plough				1		−0.8															≤	0
	Cultivate				1			−3.2														≤	0
	Drill				1				−2.5													≤	0
Required number of hours	Harvest					1				−1												≤	0
	Transport					1					−1											≤	0
	Transport					1						−1										≤	0
	Plough						1						−1									≤	0
	Cultivate							1						−1								≤	0
	Drill								1						−1							≤	0
Supplied number of hours	Harvest									1						−200						≤	0
	Transport										1						−200					≤	0
	Transport											1						−200				≤	0
	Plough												1						−150			≤	0
	Cultivate													1						−150		≤	0
	Drill														1						−150	≤	0
Machinery constraints	Comb. Harvester															1						≤	10
	Trailer																1					≤	10
	Trailer																	1				≤	10
	Plough																		1			≤	10
	Cultivator																			1		≤	10
	Drill																				1	≤	10
Obj. function																−4000	−200	−200	−300	−350	−400	≤	0

Fig 4.1 Example of a linear programming matrix using different activities of one crop for one period

period of a crop and from rainfall data during harvesting time in the Lothian region. Weather records for 24 consecutive years at the site were examined day by day; a day was designated as zero if it did not satisfy either of the criteria by Witney et al. (1982) based on the moisture content at field capacity and Glasbey and McGechan (1986) based on the amount of rainfall in the last 24 hours, as one if it satisfied only the criteria of Witney et al. and as two if it satisfied both criteria (Appendix D). The year was divided into periods by calendar date depending on the cropping system and the different operations scheduled. For each period, the numbers of days over the last 24 years were ordered from the maximum to the minimum into three sets of days depending on the quality of a day, zero for a non work day, one for tillage alone and two for tillage and harvesting (Table 4.1). At any given probability level, a cut-off point would be made to determine the available work days for each period and used in the right hand side of the matrix in terms of hours as constraints in the linear programming model. In the linear programming matrix, the number of suitable days available was converted to hours assuming that eight hours per day of work is standard except for cereal harvesting, where the number of hours per day is six hours. Half of the number of hours used per day for any operation could be used as overtime if necessary. In this study, overtime has not been taken into account, and the cut-off point has been taken at 75% probability level.

Farm operations for the complete year were organised on the basis of the number and the nature of the crop used in the rotation. Periods were determined in this study depending on the optimum sowing and harvesting dates of the crop being grown.

Table 4.1 Ordered sets of days in harvesting period of 32 days

Probability	Years	Number of workdays Unworkable 0	Tillage only 1	Harvesting or tillage 2
	1	6	27	22
	2	6	26	22
	3	5	23	20
	4	5	21	20
	5	3	21	20
25%	6	3	19	20
	7	3	18	20
	8	3	16	18
	9	2	16	17
	10	2	15	17
	11	1	15	17
50%	12	1	14	17
	13	1	14	15
	14	1	14	15
	15	0	12	14
	16	0	12	14
	17	0	12	14
75%	18	0	11	12
	19	0	11	11
	20	0	10	11
	21	0	9	10
	22	0	9	9
	23	0	8	6
100%	24	0	7	5

Machinery constraints were imposed assuming a fleet of four power sizes of tractors (45 kW, 61 kW, 74 kW, 94 kW) which had been selected using the tractor performance model (section 3). The necessary implements and machines for cereals and potatoes were matched correctly with the individual tractor size. Of all the feasible combinations of tyre dynamic loading, drawbar pull, travel speed and implement draught, there are relatively few realistic alternatives for a given tractor characterised by a particular maximum power and a set of gear ratios. The appropriate rates of work were determined for each operation using different sizes of machinery to calculate the number of hours required to complete a task (Table 4.2).

A crop is established by a tractor and different implements and machinery matched together depending on the nature of the crop and the sequences of operation required. The tractor and its corresponding implements used to perform a sequence of operations for a crop are called a set. The model can handle two approaches to the integerisation procedure; one is having a set of machines as one variable to be integerised for each size of tractor, the other is by taking each individual machine within each set as a separate variable to be integerised and the number of integer variables is then equal to the number of machines or items of equipment used in any set depending on the crop. For example, a tractor could be used to pull a potato harvester, a trailer or other implements depending on the time of the year and the availability of the machines. The assumption is made that the smallest size of tractor cannot be utilised for heavy duties such as ploughing, pulling a potato harvester or destoning the soil for potatoes. Two or more activities can be performed at the same time with machines or implements of the same set if the number

Table 4.2 Rate of work (ha/h) matched with each size of tractor for different operations

Tractor power, kW	Rate of work, ha/h				
	Plough	Cultivation	Drill	Destone	Plant
45	-	1.9	1.5	-	0.3
61	0.62	2.4	1.9	0.4	0.4
74	0.8	3.2	2.5	0.5	0.5
94	0.92	4.8	3.8	0.6	0.6

of tractor sizes corresponding to that set is selected. All machinery included in one set are matched outside the model. Sets are chosen depending on the specific operations for crops. It is assumed that all cereal harvesting operations are executed by a self-propelled combine harvester at one of two rates of work, 1.3 ha/h and 1.55 ha/h, and the potato harvesting operation by a potato harvester at a rate of work of 0.3 ha/h (two row trailed, unmanned, elevator discharge harvester). On the other hand, transportation of cereal grains and potatoes is provided by a number of trailers of the same size which can be pulled by any given size of tractor in a selected fleet. The number of trailers needed to satisfy the harvesting operations without waiting time is calculated on the basis of loading and unloading time for the transport unit, time spent travelling from the field to the storage area, time for waiting in the queue if there is one, and time for filling the grain tank and unloading the harvester (equation 2.29). In the case of the potato harvester, one trailer should be continuously alongside the machine when the other one is taking the crop back to the store; hence, a fleet of three tractors is required for the potato harvesting operation, one to pull the harvester and two for transport. In this study, the assumption of two trailers per harvesting machine is made throughout the whole year. A medium sized trailer is chosen for all operations to avoid the complexity of queueing theory and to avoid damage to the soil. The structure of the soil can deteriorate due to excessive wheel slip with a tractor operating at high torque or with high trailer loads which cause compaction. This damage is evaluated by assessment of financial losses through a crop yield reduction.

The number of men is equal to the integer number of the selected size of tractor fleet used in the model except for the combine harvester. It is assumed that cereal harvesting could be achieved by the farmer himself or one member of his family driving the machine to reduce the labour costs. Labour costs are associated with annual tractor work which have been counted as fixed costs. Labour is supplied by regular full time workers assuming an 8 hour working day with an allowance for working overtime rather than hiring additional workers during any field operation. Man machines are fully utilised on regular time before overtime is used in each time period. Fuel costs can be calculated for each activity depending on the power utilisation ratio required for any particular job.

4.1.2 Generator program (LP80P1)

The role of the generator program is essentially a format convertor. The user specifies the technical coefficients for each variable and the right hand side values for the linear program in one format, and the generator (LP80P1) then converts them to the standard form. In this case, the input data information in the original matrix has been converted into two outputs (stream 2 and stream 3) which are respectively a printable copy of the converted matrix and a computer file to be used to obtain a solution to the linear programming problem (Fig 4.2). The solution can alternatively be obtained by applying duality theory, since every linear programming problem has associated with it another linear programming problem called the dual (Table 4.3). This is helpful since some problems are easier to solve row by row instead of the usual column by column approach adopted by linear programming packages.

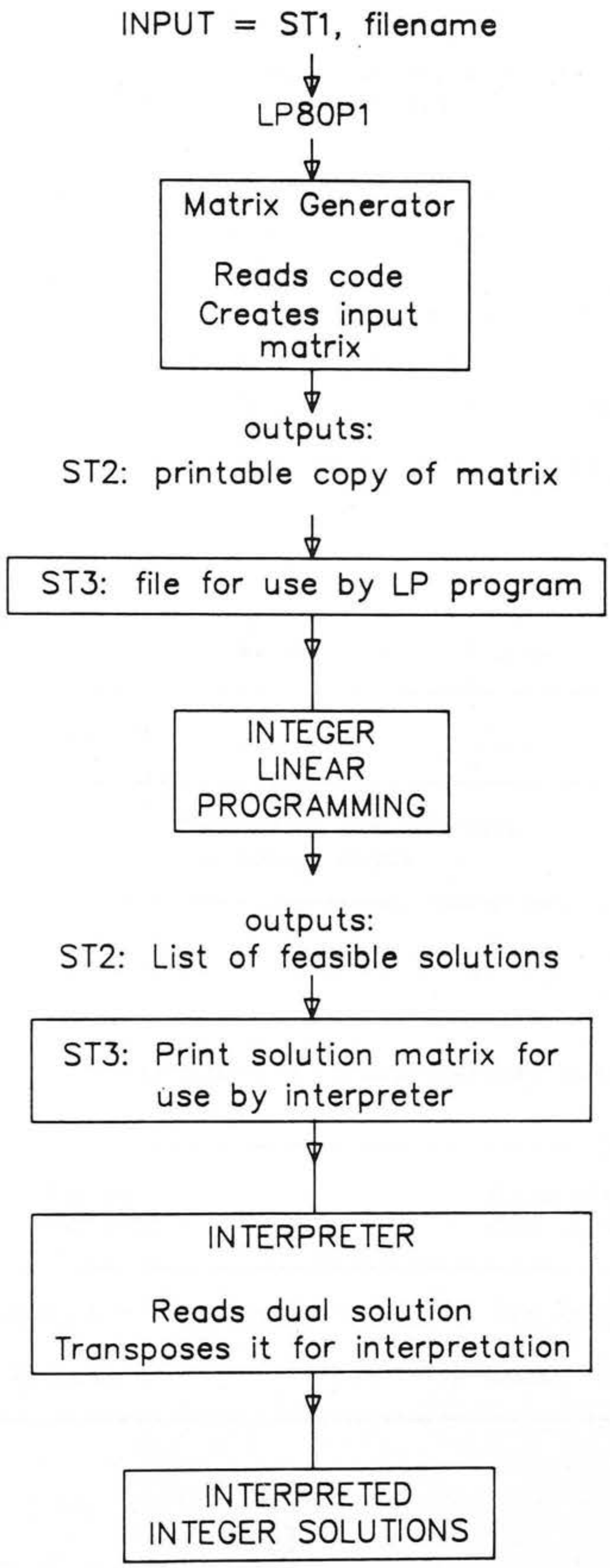

Fig 4.2 General flow diagram of mixed integer linear programming model

Table 4.3 Primal dual table for linear programming (after Hillier and Lieberman 1974)

PRIMAL PROBLEM

		Coefficient of X_1	X_2.............X_{nr}	RHS Primal	
DUAL PROBLEM Coefficient of	y_1	a_{11}	a_{12}...........a_{1nr}	$\leq b_1$	Coefficient for objective function (Max)
	y_2	a_{21}	a_{22}...........a_{2nr}	$\leq b_2$	
	y_{mc}	a_{mc1}	a_{mc2}..........a_{mcnr}		
RHS	Dual	$\geq C_1$	$\geq C_2$ $\geq C_{nr}$		

Coefficient for objective function (Min)

Table 4.4 Relationships for complementary basic solutions

Primal variable		Associated dual variable
Basic	<----------------------->	Non basic
Non-basic	<-------------------->	Basic

Primal problem

Find $X_1, \ldots ; X_{n_r}$ so as to

minimise objective function

$$Z_r = \sum_{e=1}^{n_r} C_1 X_e \qquad \ldots 4.1$$

subject to

$$\sum_{e=1}^{n_r} a_{ie} X_e \leq b_i \text{ for } i = 1,2,\ldots m_c \qquad \ldots 4.2$$

$$X_e \geq 0 \text{ for } e = 1,2,\ldots n_r$$

where C_1 = the price of the e^{th} activity in the objective function, £;
a_{ie} = the technical coefficient for the i^{th} constraint and the e^{th} activity;
X_e = the e^{th} activity level;
b_i = the resource available in the i^{th} constraint;
Z_r = the objective function.

Dual problem

Find $y_1, y_2, \ldots y_{m_c}$ so as to

maximise objective function

$$Z_r = \sum_{i=1}^{m_c} b_i y_i, \qquad \ldots 4.3$$

subject to

$$\sum_{i=1}^{m_c} a_{ie} y_i \geq C_e \text{ for } e = 1,2,\ldots n_r \qquad \ldots 4.4$$

$$y_i \geq 0 \text{ for } i = 1,2,\ldots m_c$$

where y_i = the i^{th} constraint level.

An error check is also performed and provided for in the program and default data are used to complete the data set.

The simplex method can be applied to either the primal (original) or to its dual problem and still identify an optimum solution. If the primal problem has (n_r) functional constraints and (m_c) variables, then the dual must have (m_c) constraints and (n_r) variables. There are two phases for the simplex:

1. to establish an initial feasible basis,
2. to optimise.

Given that, the C_e prices are all negative in the primal but in the transpose the C_e are all positive. The condition for an initial feasible solution is that the right hand side is non-negative. Hence the optimisation of phase two can commence immediately in the dual mode (Table 4.4).

4.1.3 Integerisation of the linear programming model

Method

In many practical problems, the decision makes sense only if there are integer variables in the solution. It is necessary to assign machines, men and tractors to activities in integer numbers. In linear programming problems, some progress has been made towards development of a method which is subject to an individual restriction that some variables in the solution must be integers. A separate program is written (INTEGER) to have the output stream 3 of the previous program (LP80P1) as an input. It uses the simplex method ignoring the integer restriction. In the INTEGER program (Appendix C2) a branch and bound method is used as a partial enumeration method to solve mixed integer linear programming problems. The original work on this is due to Land and Doig (1960). The method started by optimising the problem as normal and usual by ignoring the integer requirements. This first optimal solution becomes the starting point of the branching method. If the solution to the continuous problem contains integer variables at new integer values, then one of them is selected to generate two new branches. These branches define two new issues. In the first of the two new problems, the integer variable being branched is bound so as to take only a value less than or equal to the integer part of its present level. In the second, the integer variable being branched is bound so as to assume only values greater than or equal to the smallest integer greater than its present level. The program creates automatically a backing list of problems to be solved, whilst the other is optimised. An analysis of the optimal solution is carried out to determine if it is non feasible, or feasible and integer, or feasible and non integer (Fig 4.3). If it is not feasible, the branch is terminated and the next problem from the backing list is recovered and optimised. If it is feasible and integer, the solution becomes the best integer solution so far. The process is carried on to find any better solution than the first to the problem by analysing all feasible and non integer solutions with a value less than the integer solution found. If it is feasible and non integer, this solution becomes a node for branching and two more branches are created, one of which is added to the backing list while the other is optimised. The procedure is repeated until all the problems on the backing list with lower costs are less than that of the best integer solution already found. The program stops automatically at the end of the iteration in which the best feasible integer is found or at the end of the feasible solution analysis. The INTEGER program as LP80P1 is analysed in the dual; it creates two outputs in streams 2 and 3 respectively to list a summary of feasible solutions (integer and non integer) and a print-out of the best integer solutions en route to the optimum which can be used by the interpreter program.

Procedure:

After declaring all integers, reals, real arrays, integer arrays and numbers used, the model:

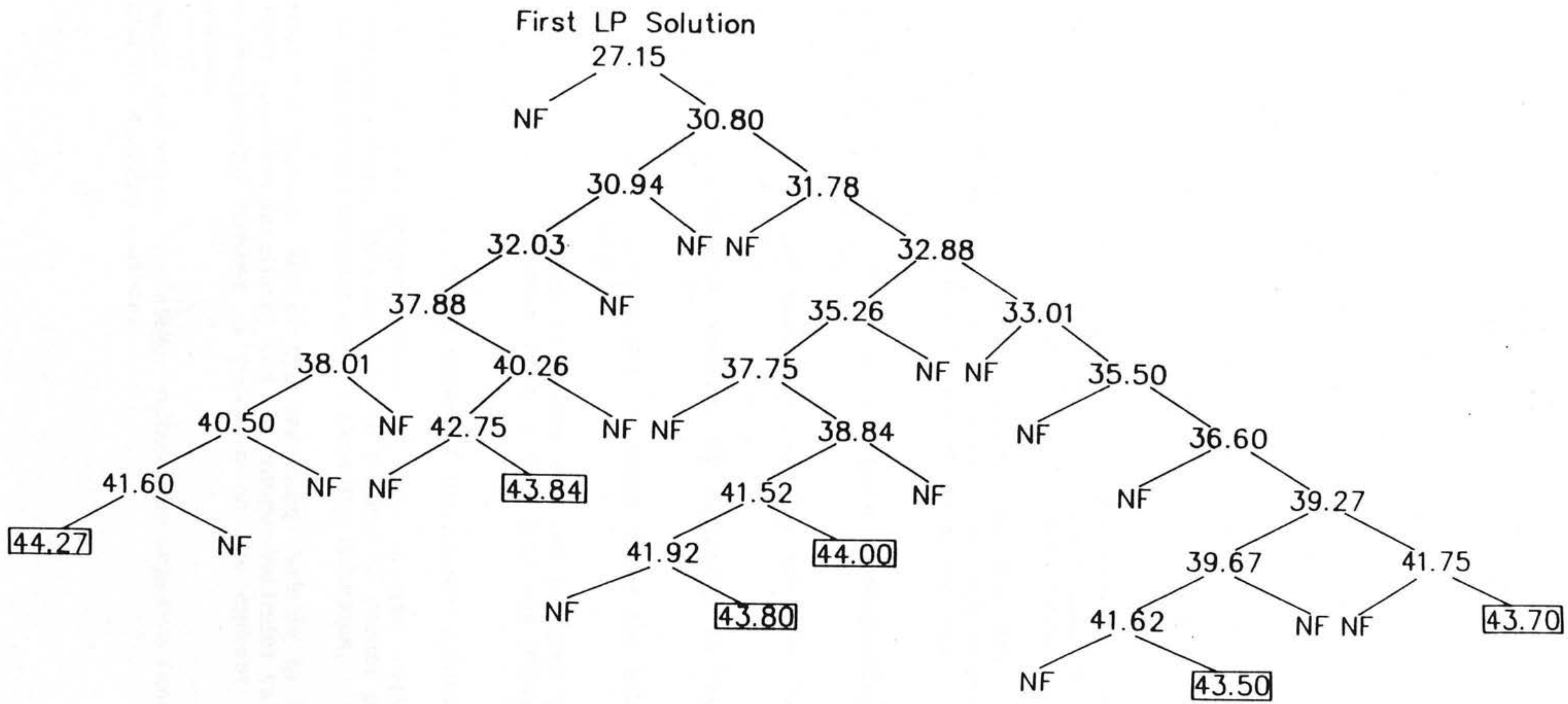

Fig 4.3 Integer linear programming solutions using branch and bound method

NF = non feasible
□ = integer solutions obtained

- reads all the initialised parameters written in the selected output of the previous program (LP80P1);
- reads the initial input matrix, stores and alters it in the dual process by changing the sign of the whole column;
- operates conventionally the linear program to find a feasible solution by pivoting the matrix and optimising the solution;
- avoids exceeding the length of the list of problems by including a fail-safe device;
- reads the input matrix by writing the iteration number, the objective function value of the last integer solution found, and the objective function value of the previous solution;
- reassigns integer restraints, stores the full list of restraint values initialised to a given value (-10) and overwrites after each solution one list with the minimum and one list with the maximum;
- writes the integer restraints and their corresponding objective values on the waiting list;
- solves the matrix and assigns a negative value to the objective function of the dual;
- indicates a non-feasible solution by assigning to the objective function a given value;
- writes the correct information in output 3 for the interpreter if the solution is integer;
- selects the next problem by adding two new problems to the list, if the objective function value is less than the integer solution obtained;
- writes the integer restraint values of the present solution added;
- saves the non-integer values of the integer variables and reassigns them, then assigns the number of parent problems of the non solved problem and its objective functions;
- writes the current list of the remaining variable to be solved, their objective functions, and the integer restraint values of the corresponding number of problems on the current list to be solved;
- assigns and stores the integer values, the objective function value and its iteration number.

If the new integer solution is less than the previous, it assigns it, writes it and continues. If the new solution value is less than the current objective function value, then it stops and selects the next problem. If the new integer solution is less than the previous one, then it continues to route the iteration number and the objective value.

For any solution, it selects the least value of the parent for the next iteration; if the current value of the objective function is lower than the last integer solution, the job is terminated.

4.1.4 Interpretation of the solution

The interpreter, which is the third program in the linear programming suite named LP87PR, (Appendix C3), takes the output in stream 3 of the INTEGER program which is the previous program, as its input (solution matrix). The interpreter reads the dual solution from INTEGER, then transposes them to the primal (original form) for interpretation. The interpretation is summarised by the area of each crop, the objective function, the field operation schedules and the time and overtime spent for each operation, production activities and shadow prices. The interpretation is divided into two sections which are: basic variables and non basic variables.

Basic variables:

There are two types: selected activities and slack (not used). The unused activities are the surplus remaining from the activities applied in the matrix where a restraint is not binding. The surplus or the unused activity is called slack which can be defined as the length of time an activity can be delayed without affecting the completion date from the plan, or the number of the sets in surplus which can be added without any change. A selected activity in the basic variables could be a value of the time required to achieve an operation, a number of sets required to do the operation, and the area for each crop grown within the year. If a given resource is absorbed completely by the basic variables (selected), the slack is zero. The interpretation of the solution could be cost minimisation or profit maximisation. In this case, the solution is treated as a cost minimised. The initial objective row has negative values. After the pivot operation which is the interchange of a row variable for a column variable, the new matrix is constructed. Dividing the negative elements in the objective row by the corresponding positive values from the matrix in the row of the selected activities to get the minimum price rise that changes the solution. Again, the ratio of negative elements of the objective row to the corresponding negative elements from the same row of the selected activities gets the minimum price fall that changes the solution. The upper and lower limits of the permissible range are just the value of the change that could be greater than the lower limit and less than the upper limit. The two limits are determined by adding the price change value in each case to the corresponding initial negative value of its objective row. The percentage increase or decrease in the change is the ratio of the change in price in either direction to the initial value of the objective row of a selected activity.

Non basic variables:

There are two types: non selected activities (excluded activities) and binding restraints (limiting resources). The requirement for the non selected activities is to determine the change of price needed to convert an excluded activity to an activity which is used in the solution. The change in price value is given by the shadow price which is the marginal value product of a non selected activity. The right hand side is divided by negative coefficients in the column and the one with the minimum modulus limits the substitution to find the units worth to get an additional variable to the selected.

Binding restraints: the extension of a decrease in the limiting resource before a change in the basis takes place, could be done through a ratio of the right hand side to the negative coefficients and getting the minimum modulus. The units that can be withdrawn before drawing a selected variable from the solution can be determined. Similarly for the extension of a resource, an increase in the objective function could be done by the marginal value product for each unit of the resource. The limiting resource is determined from the positive coefficients. If the resource can be purchased for less than the marginal value product, the number of extra units it would be worth purchasing should be known.

4.2 Cropping simulation

4.2.1 Markov process

The sequence of wet and dry days is critical for the simulation of sequential field tasks. Simulation of run lengths of wet days, precipitation on wet days and run lengths of dry days depending on the season was calculated using a Markov model (Appendix E). This technique is useful for generating sequences of days. When aggregating days into periods, the autocorrelation between one day and the next is lost. This indicates that there is no relation between rainfall at different times within a season. Using the 24 years sequence in a period of 32 days during harvest time (July-August) as an illustration, commencing with the day before, this could be a work day or non work day. The workability depends on weather and soil moisture content conditions. A model was developed by Witney et al. (1982), in which the criteria used to produce the difference between a work day and non work day soil condition depended on the moisture content of the top 30 cm soil layer, the amount of daily precipitation, and the daily air temperature. The model balances the quantity of water gained by the soil against the quantity of water lost from the soil. The soil moisture was calculated in terms of a percentage of field capacity of the soil. If the moisture content on a particular day was below the established criterion, the given day is considered as a workable day. If the soil moisture content was above the criteria, the day is considered as non workable. The model was extended by taking into account harvesting workability. The criterion for harvesting days depends on the quantity of rain falling in the previous day. If the previous day was a work day and on the current day precipitation did not exceed 1.4 mm, the day is considered as a harvesting day. As has been mentioned in section 4.1, the days are classified as day zero, day one or day two depending on the criteria they satisfy. The Markov matrix can be constructed from the frequency of occurrence of the work day/non work day phenomena (Table 4.5). If the previous day is a non work day there is a 20/40 chance that the current day will be a non work day. If the previous day is a work day there is only a 22/728 chance that the current day will be a non work day. A second random

Table 4.5 Frequency of work and non work days

A summer period (24 years x 32 days)

Current day	Previous day No work 0	 Work 1
No work 0	20	22
work 1	20	706
Total	40	728

Table 4.6 Frequency of tillage only and harvest days

A summer period (24 years x 32 days)

Current day	No work 0	Previous day Tillage only 1	Harvest 2
Tillage only 1	10	230	120
Harvest 2	10	124	232
Total	20	354	352

number process is added to convert some days from one into day two (based on Table 4.6). If the current work day is a work day, a matrix is constructed to classify the day into tillage only or harvest only, since they are mutually exclusive. If the previous day was a non work day, there is a 10/20 chance of either tillage or harvest being done. If the previous day was for tillage, the persistency factor is high at 230/354 chance to till and 124/354 chance to harvest. Similarly if the previous day was a harvest day, the persistency factor is again high at 232/352 chance to harvest and 120/352 chance to till. Such a process will produce patterns of work days for all similar periods of the year but not identical with the historical records used in section 4.1.1 to determine the available workdays in the right hand side of the linear programming matrix. The historical records are used as an input of the Markov model to generate sufficient output to be used for crop simulation and to draw smoothed cumulative probability distributions suitable for stochastic dominance analysis.

4.2.2 **Simulation procedure**

A large model was developed to simulate a four crop rotation system for several years (Appendix F). The model is designed to conduct analysis of the economic revenue from machine operations depending on the generated weather patterns. The model is divided in several periods depending on a different combination of planting, sowing or harvesting dates. The period is named in alphabetical order. The operations are described in the period where they take place (Table 4.7). The program is initialised with data to simulate the rotation system under a sequence of generated days. The required information used as input data are:

Table 4.7 Arable farming year East of Scotland

Name	Days	Period	Precedence	Operation	Optimal dates
A	32	218-249	1	Harvest w.barley	Aug 7
			2	Plough	
			3	Cultivate	
B	17	250-266	1	Harvest sp.barley	Sept 7
			2	Plough	
			3	Cultivate	
			4	Drill w.barley	Sept 15
C	28	267-294	1	Harvest w.wheat	Sept 25
			2	Drill w.barley	
			3	Lift potatoes	Oct 14
D	42	295-336	1	Lift potatoes	Oct 14
			2	Cultivate	
			3	Drill w.wheat	Oct 23
E	29	337-365	1	Plough	
F	63	01-63	1	Plough	
G	28	64-91	1	Cultivate	
			2	Drill sp.barley	March 18
H	49	92-140	1	Destone	
			2	Plant potatoes	April 14
I	77	141-217		Miscellaneous non limiting tasks. Spray, fertilise...etc	

- frequency of work and non work days for tillage and harvesting for each period using the Markov method;
- area of each crop used in the rotation system, in hectares;
- expected yield in tonnes per hectare for each crop;
- coefficient of timeliness penalties for sowing and harvesting earlier or later than the optimum date;
- optimum date of sowing or planting of each crop used;
- optimum date of harvesting of each crop;
- number and rate of work of each machine and item of equipment used;
- area sowed or planted by day and the day number in which it has been done as initiation dates.

After the input data are read, the program calculates the total rate of work of each operation depending on the rate of work of the individual machine chosen multiplied by the number needed to perform the job. Before the first year of the simulation commences, the weather is generated by a temporary simulator for the initiation data assuming it as year zero. Each period is delimited by its starting and finishing day. The number of days within a period are simulated day by day using the input frequency of work days (Markov chain).

The first period named A is the period starting with harvesting the first ripe crop which is winter barley. It is the first operation of the farm plan with an optimum day of ripeness at 7 August. The optimum day is taken as the starting day and the latest finishing day is the previous day of the optimum day of harvesting the next ripe crop, but it could be finished before. The operations which occur in period A with harvesting are ploughing and cultivating the harvested area of winter barley. Available tillage days are greater in number than harvest days but they can be conditional on land being harvested first. Land restraints can be used to achieve this purpose requiring the combined operations to be done within the constraint. This takes no account of the precedence requirement when different criteria are involved. In any harvest period, tillage days will be available if the harvest days appear first in the sequence of generated weather days but generally fewer days are available due to the distribution of harvest days throughout the period. Some good tillage days are lost because there is no harvested land available to till. The deviation of time as a timeliness penalty affects the yield of the crop. On the other hand, if harvesting is finished early the unused harvest days are donated to the tillage constraint row. Work commences on entering each period engaging the tasks in order of precedence (Fig 4.4). The dates of sowing and the dates of harvesting are logged for blocks of each crop. Block size is determined by the area planted on a particular day. Timeliness penalties are applied to each block and aggregated for the whole crop. For a given duration, an average yield loss, starting an operation before the optimum day for planting or at the optimum day for harvesting and finishing was calculated by the equation 2.34 with the relevant timeliness coefficients for early and late establishment and late harvesting. The ripeness of a crop cannot be in a single day, therefore a percentage of loss has been added to the equation as a constant loss at maturity. The actual and the expected total yield were determined to calculate the harvesting losses. The total losses are given by the sum of planting losses and harvesting losses of the winter barley crop.

Period B starts from the optimum date of harvesting spring barley (7 September) to the day before the optimum date of harvesting the next crop of the rotation. Spring barley is the second crop to ripen in

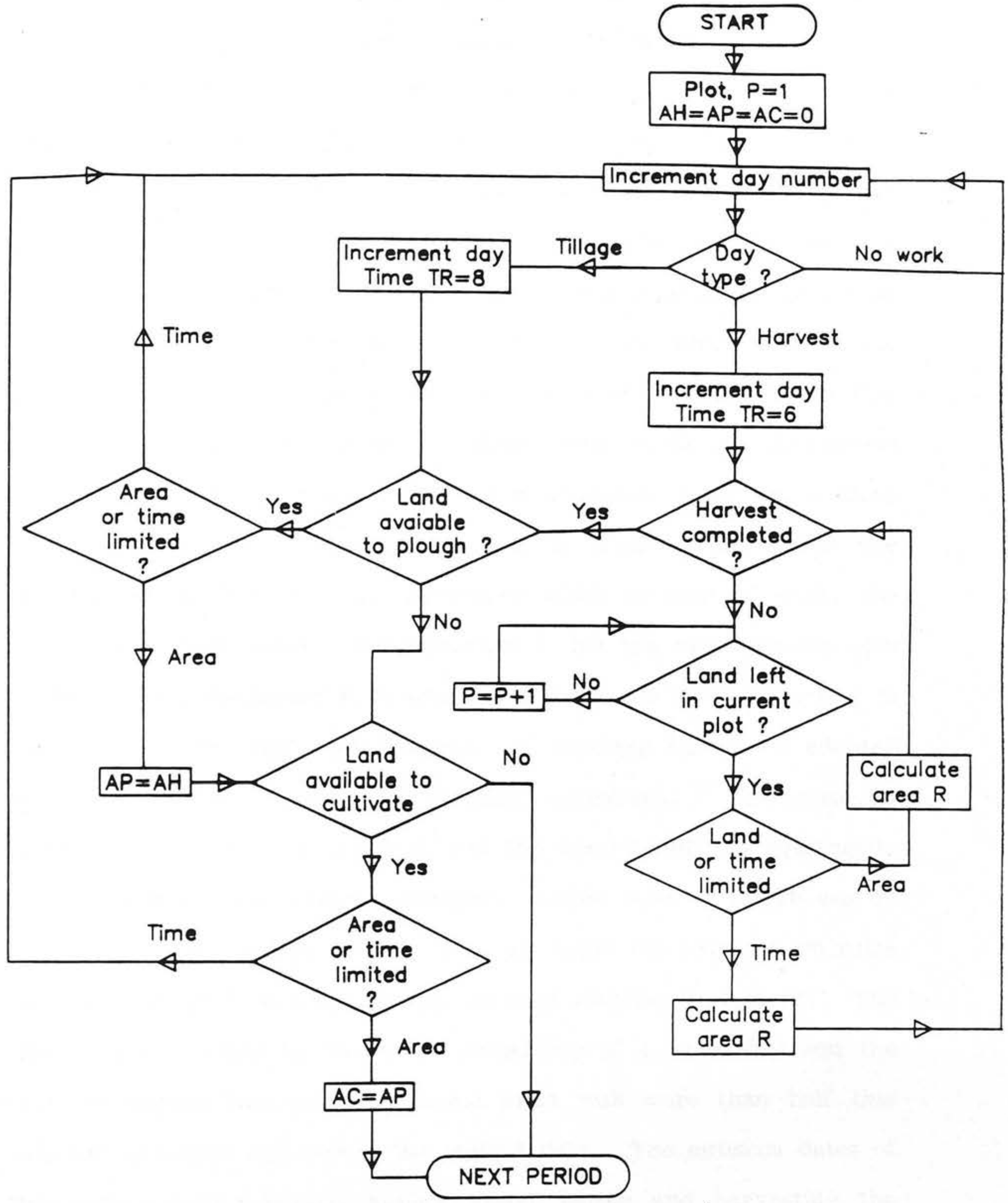

Fig 4.4 Flow chart representing harvesting, ploughing and cultivating activities in period A

the system. The harvesting, ploughing and cultivating scenario continues in the same manner and sequence as in period A. Half of the winter barley area harvested, ploughed and cultivated in period A plus the area of spring barley harvested, ploughed and cultivated in period B has to be planted with winter barley at an optimum date of 15 September. Timely operation has a major effect on the economic strategy of the whole enterprise. Late establishment of an arable crop disturbs the germination cycle of the crop which affects the growing season and decreases the potential yield. It is evident that delays in planting have to be minimised since yields are determined directly from the planting dates. The expected yield has a close dependence on the planting date. It is often assumed that the greater the tractor fleet and machinery width or rate of work, the smaller the yield losses. However, this is not the case because with large capacity machinery it is possible to plant too early according to the shape of the crop loss function. A strategy has to be adopted regarding starting dates for planting operations. The strategy depends on the size of the task and the capacity of the equipment. This determines the required timespan. Simple rules of thumb can be employed to ensure that planting does not begin too soon. Such rules improve the performance of large capacity planting equipment. The timespan is divided by the prior probability of a work day and the rule is applied that planting cannot start with more than half this number (rounded up) before the optimal date. The optimum dates of harvesting spring barley, sowing winter barley and harvesting the next crop are very close to each other. They should all take place within two weeks. It is difficult to perform the complete tasks in bad weather due to the reduced number of harvesting days within the period. All the operations in period B, such as harvesting, ploughing, cultivating and sowing can be carried out in the next period, depending on the spring barley harvesting activity at the end of period B. If the harvesting operation could be finished in period B, the rest of the activities in period B such as ploughing, cultivating and drilling, or cultivating and drilling if ploughing is finished, or just drilling if both ploughing and cultivating are finished in B, can be carried out in period C depending on the workable days remaining after harvesting spring barley. If the harvesting operation is not completed in period B, this affects the activities of period C by delaying the optimum date of harvesting winter wheat, and delaying the potato harvesting. A delay in harvesting potato delays the optimum date of sowing winter wheat in period D. The number of operations in period C becomes first finishing spring barley harvesting operation, then harvesting winter wheat, then ploughing, cultivating or drilling any spring barley area harvested in any workable days suitable for tillage between the two harvesting operations, continuing ploughing, cultivating and drilling then lifting potatoes. The decision to continue the harvesting operation in period C depends on the varieties of the crops, the area of the two crops, the slopes of the losses curves, and the percentage of losses at a particular day. Fig 4.5 shows the overlap of harvesting barley and wheat. The slope of the curve of barley is sharper than the slope of the curve of wheat. The losses of barley are much higher than winter wheat. In this study the operations of period B are carried out in period C. If the farmer decides to stop harvesting spring barley to start harvesting winter wheat at its optimum date, the area still to be harvested is considered lost which changes the rotation

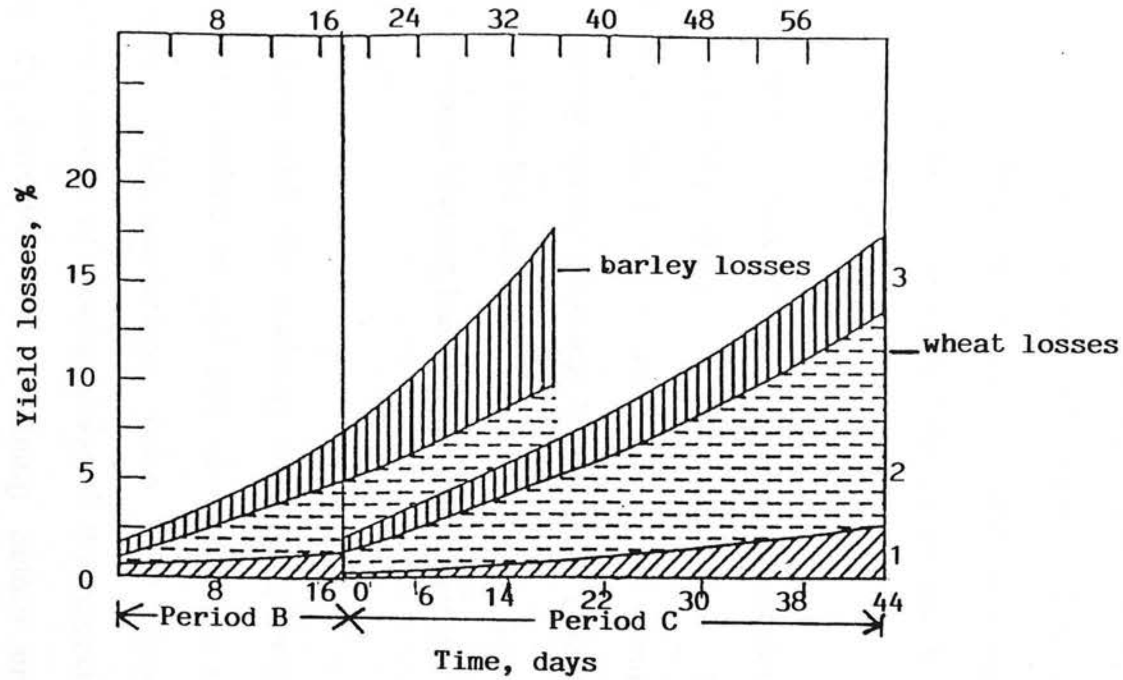

Fig 4.5 The overlap of harvesting losses of barley and wheat in period C
1 - dry matter loss; 2 - shatter loss; 3 - combine header loss

system by reducing one crop and increasing another. The sowing area of winter barley is decreased because the drilling operation is not finished, which affects the next year's crop.

Period C starts normally with the optimum date for harvesting winter wheat (25 September) and finishing a day before the optimum date for drilling winter wheat for the next year. The operations which take place in this period are harvesting winter wheat and potatoes. In case of bad weather, the operations of period B are carried over, as has been mentioned above.

The spring barley harvesting losses were calculated depending on the delay in harvesting after the optimum date. Then the actual and expected total yield were determined to calculate the harvesting losses. Spring barley planting losses were calculated on the basis of the optimum date for planting the crop. The total losses are equal to the sum of losses during harvesting and planting periods which affect the crop yield.

Period D starts with the optimum date for planting winter wheat (23 October) and finishes at the end of completion of the operations of this period. The operations which take place in period D are finishing the harvest of winter wheat if the operation is not completed in period C, finishing the remaining potato crop, cultivating the harvested potato area and drilling the winter wheat. Winter wheat follows potatoes in the rotation, therefore the crop cannot be sown if the potatoes remain in the ground. The potato harvesting operation is slow with a rate of work of 0.3 ha/h, therefore the optimum date of drilling winter wheat could be delayed to the end of November. Planting and harvesting losses for winter wheat and potatoes were determined. The expected and actual total yield of each crop were calculated. Then the total losses for each crop were determined. Period EF is a less busy period of the year in which the ploughing operation occurs. Potatoes and spring barley are the two crops which remain to be established. Spring barley follows winter wheat area harvested in period C and potatoes substitute half of the winter barley area harvested in period A. This period is called EF because it covers two sub periods, one being located at the end of the year and the other belonging to the starting period of the new year.

Period G starts with cultivating the two crops ploughed previously in period EF and contains the drilling operation of spring barley with an optimum date at 18 March. Period H consists of destoning and planting the potato crop with an optimum date of planting at 14 April. The last period closes the cycle of activities performed during the year in a different period with different lengths. This period is left to miscellaneous activities with non limiting tasks. Any activity like spraying, fertilising, grass cutting, forage harvesting can occur. Endless simulation of 100 year cycles is carried out using a process built specially for each period. The results are summarised in the form of annual losses for the four crops used in the simulation process (Appendix G). The stochastic dominance technique can be used to rank the cumulative probability distribution of expected farm income resulting from the operation of each selected machinery set. The only source of variation is that due to the timeliness penalties. The expected farm income is obtained by subtracting the total yield loss value of the crops from the maximum yield value. The maximum yield value is equal to the total yield of the crop multiplied by the value per tonne of the crop. The total yield is obtained using the product of the area and the maximum yield of the crop in tonne per hectare. The total yield loss value is equal to the price of the crop per tonne multiplied by the results of the losses of the crops obtained from the simulator for the 100 year period. The expected farm income obtained each year is ordered from the maximum to the minimum value through the length of the simulator run to draw a cumulative distribution graph for any selected set of machinery. The deviation between different cumulative distributions can be seen in bad weather.

4.2.3 Farming risk

Management risk in selecting machinery sets is high because of the uncertainty of the weather conditions. The climatic conditions influence timeliness of operations which becomes a crucial problem for farmers and managers. To determine an efficient and undominated set of machinery beyond a range of sets for rotation strategies, the first and second stochastic dominance degrees are used in this study to aid in risk decision analysis.

Risky prospects method

Let E, F, G and H_o be risky prospect functions uniformly distributed on the axis as the net financial outcome (Fig 4.6).

The symmetry of the functions is represented by the median which could be the mean. The two functions E and F have an identical mean, but F has a smaller variance than E, therefore E has to be discarded. To satisfy the risk efficiency requirement, the selection prospects have to be with the minimum variance for a given level of expectation. The mean of function G is greater than that of function F but the variance of F is less than that of G, therefore F cannot be eliminated from the efficient set. On the other hand, the mean and variance of function H_o are less than the mean and variance of functions F and G, but the cumulative probability functions of F and G lie entirely to the right of function H_o. In this case, H_o is stochastically dominated in the first degree by both functions F and G. The cumulative probability function of H_o will never be selected in preference to functions F and G.

$$F(x) \leq H_o(x), \text{ and} \quad \ldots 4.5$$
$$G(x) \leq H_o(x)$$

In cases where the functions intersect, the requirements of the second degree of stochastic dominance will be that the area under the cumulative probability function F should be less than or equal to the area under G. This property of second degree dominance would be demonstrated by all functions intersecting function G from below with small variance and with a mean greater than or equal to the mean of function G.

Any interval $[a_1, b_1]$ which contains the risk efficient cumulative probability functions can be enclosed by transformation to a square of unit length. The interval $[a_1, b_1]$ becomes $[0,1]$ (Fig 4.7). The second order of stochastic dominance in the interval $[0,1]$ can be expressed mathematically as:

$$\int_o^1 G(\alpha)d\alpha - \int_o^1 F(\alpha)d\alpha \geq 0 \quad \ldots 4.6$$

The risk efficient set would contain some members such that the area under the cumulative function F is less than the area under G for low values of the variable α, and some such that the area under F is greater than the area under G for high values of α. Function F could

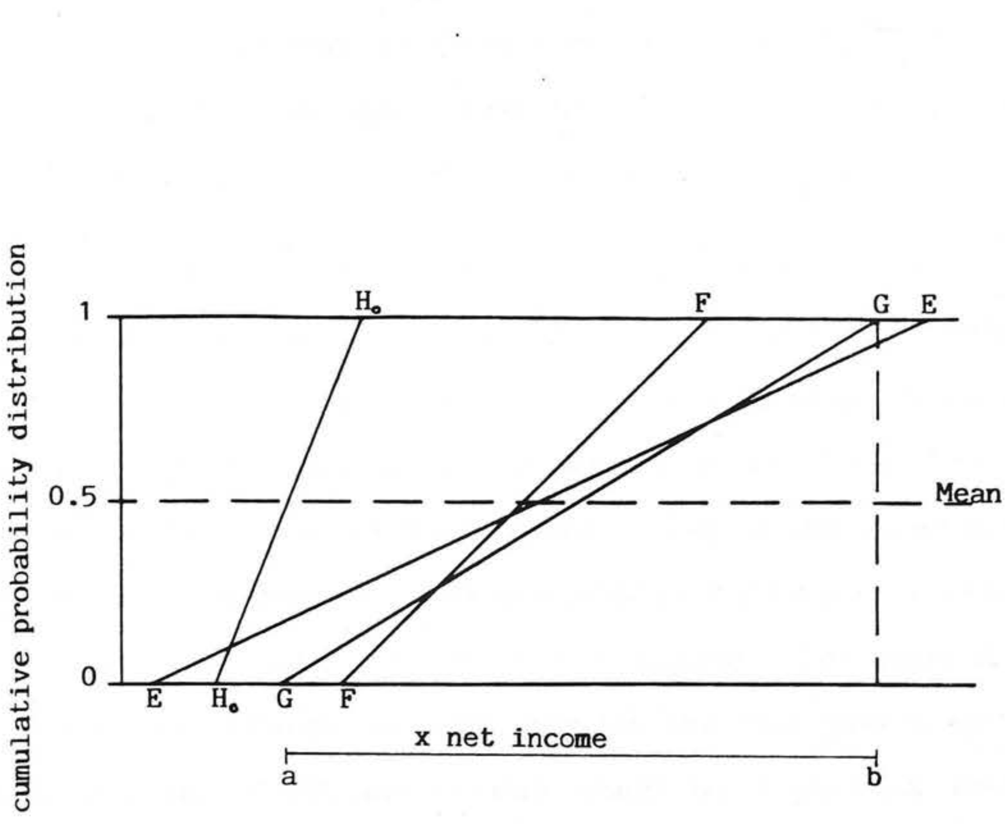

Fig 4.6 Display of alternative risky prospects

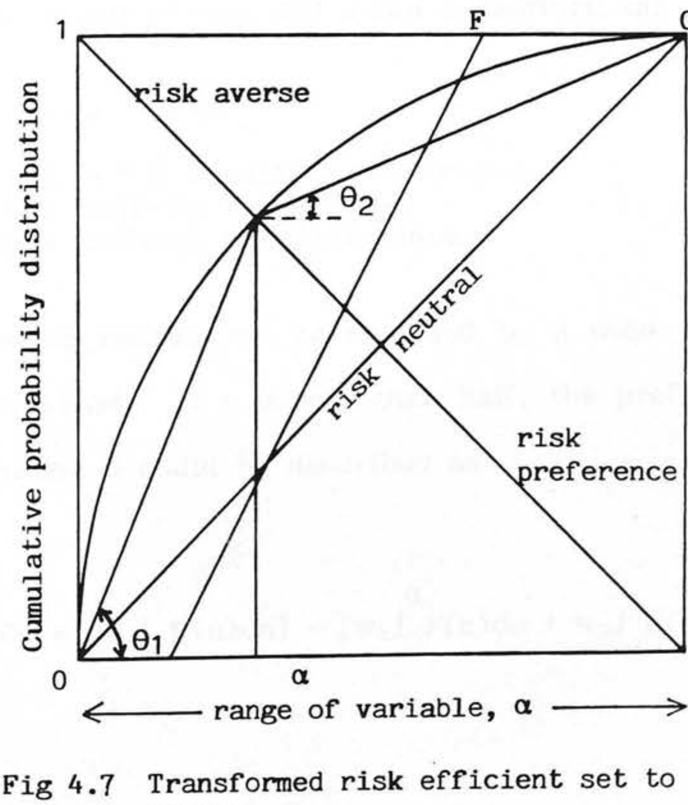

Fig 4.7 Transformed risk efficient set to a unit square

be preferred to function G by those persons to whom the income value over the lower range is higher than the income value over the higher range. They could be described as risk averse persons.

For the purpose of ranking a set of risky prospects on a scale, the attitude of the decision makers to risk is known as: risk aversion, risk neutral, or risk preference. The risk neutral function is represented by the diagonal of the square in Fig 4.7. The risk aversion function is characterised by the convex on the upper part of the diagonal of the square. Risk preference function is characterised by the concave on the lower part of the diagonal. The diagonal is a symmetrical line between the risk aversion and risk preference. A suitable measure of attitude to risk would be 0 for risk neutral, positive values between 0 and one for risk preference and negative value for risk aversion with a limited value such that:

$$-1 < \rho < 1 \quad \text{in} \quad [0,1] \qquad \ldots 4.7$$

ρ is the coefficient of risk and α can be defined as:

$$\rho = 2(\alpha - 0.5) \qquad \ldots 4.8$$

when $\rho = 0$, $\alpha = 0.5$ reflects risk neutral
$\rho < 0$ reflects risk averse
$\rho > 0$ reflects risk preference

The preference method can be analysed by a wide variety of relative weighting systems. If α is less than half, the preference of function F over function G could be described as:

$$[w_1\int_0^{\alpha} G(\alpha)d\alpha + w_2 \int_{\alpha}^{1} G(\alpha)d\alpha] - [w_1\int_0^{\alpha} F(\alpha)d\alpha + w_2\int_{\alpha}^{1} F(\alpha)d\alpha] \geq 0 \quad \ldots 4.9$$

A relative weighting system in the risk averse case is limited to a range of α between 0 and 0.5. Now the weighted values w_1 and w_2 respectively in each side of a value of α in the interval [0,1] could be determined as minima by the equality of the above equation. In Figure 4.7, the angles Θ_1 and Θ_2 to and from the intersection of the vertical line through α value on the absissa and diagonal (0,1)(1,0) constitute the pair of weighted values such that:

$$\frac{w_1}{w_2} = \frac{\tan \Theta_1}{\tan \Theta_2} = \frac{(1-\alpha)^2}{\alpha^2} \qquad \ldots \ 4.10$$

The equation 4.10 is determined trigonometrically as a function of α. The different types of attitudes towards risk can be determined using equation 4.10, but in the case of stochastic dominance, only the risk aversion method is considered. In the example illustrated in Figure 4.8, function G has a greater expectation than function F. It could be chosen by an indifferently risky person. Since function F has a lower variance, there will be a certain degree of risk aversion at which function F will be preferred. The degree of risk aversion can be determined graphically as is shown in Figure 4.8. If α is greater than 0.5, the attitude of risk becomes risk preference and the concave part of the diagonal is considered as having a positive coefficient of risk.

In sets of two or more functions (Fig 4.8) it is more interesting to establish a range of values for the coefficient of risk aversion ρ over which the function of the risk efficient set becomes the preferred choice, as long as:

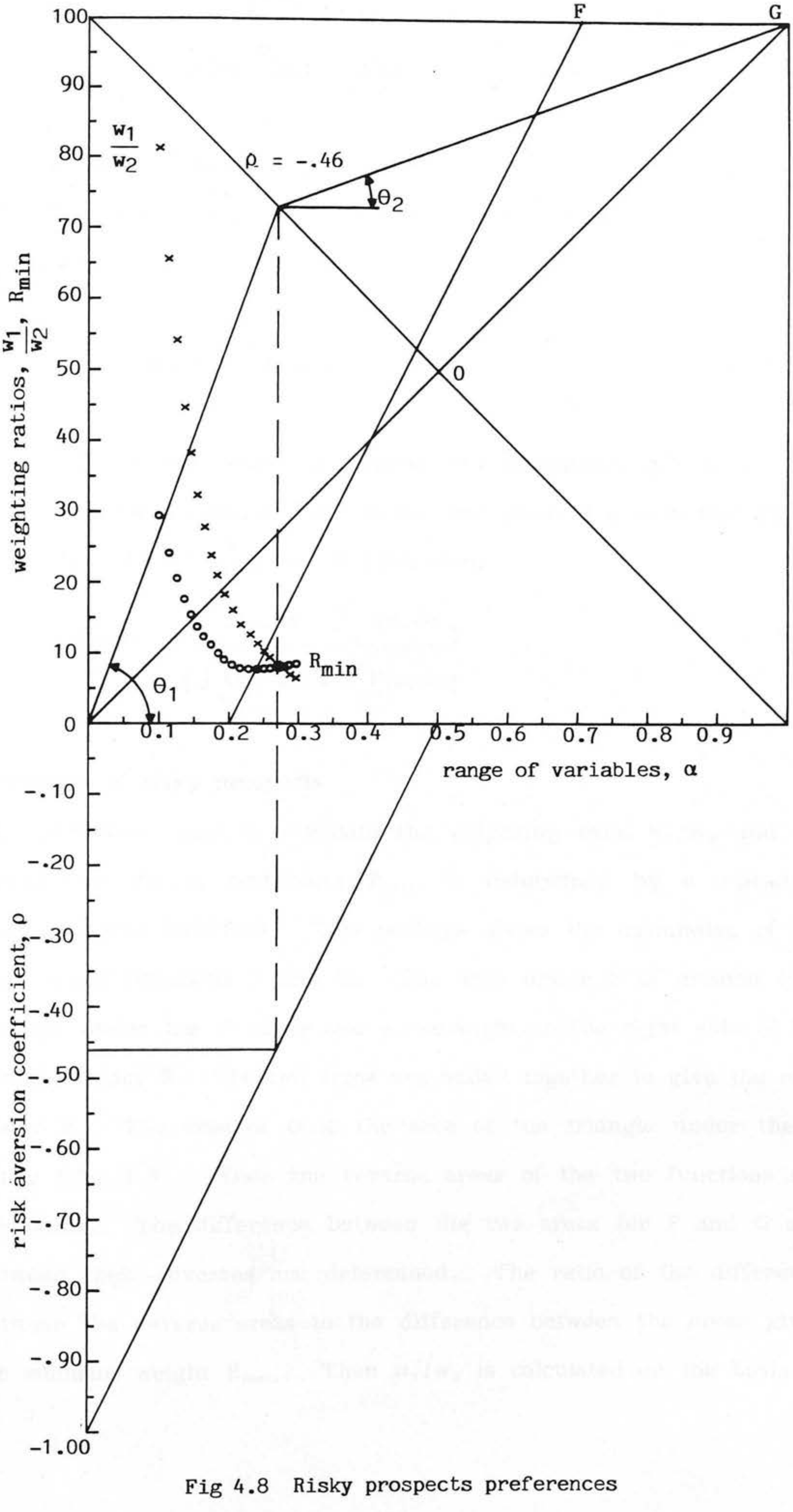

Fig 4.8 Risky prospects preferences

$$\int_0^\alpha F(\alpha)d\alpha < \int_0^\alpha G(\alpha)d\alpha \quad \text{and} \quad \int_\alpha^1 F(\alpha)d\alpha > \int_\alpha^1 G(\alpha)d\alpha \qquad \ldots 4.11$$

For the two inequalities, a minimum weighting ratio of R_{min} can be calculated to choose F in preference to G if and only if the following equality occurs:

$$\int_0^\alpha F(\alpha)d\alpha = \int_0^\alpha G(\alpha)d\alpha \qquad \ldots 4.12$$

where no positive weighting system can accomplish the task. By integrating the functions F and G for any value of α such that $(0 < \alpha < 1)$, the value of R_{min} can be calculated:

$$R_{min} = \frac{[\int_\alpha^1 F(\alpha)d\alpha - \int_\alpha^1 G(\alpha)d\alpha]}{[\int_0^\alpha G(\alpha)d\alpha - \int_0^\alpha F(\alpha)d\alpha]} \qquad \ldots 4.13$$

Procedure of risky prospects

The procedure used to calculate the weighting ratio w_1/w_2 and the minimum weighting coefficient R_{min} is determined by a statistical package called MINITAB. This package allows the calculation of the area under functions F and G. The area under F is divided in a triangle under the F curve and a rectangle on the right side of the triangle under F. The two areas are added together to give the area under F. The area of G is the area of the triangle under the G curve (Fig 4.8). Then the reverse areas of the two functions are calculated. The difference between the two areas for F and G and between their reverses are determined. The ratio of the difference between the reverse areas to the difference between the areas gives the minimum weight R_{min}. Then w_1/w_2 is calculated on the basis of equation 4.10. The two curves obtained R_{min} and w_1/w_2 are plotted on the same coordinate scale. The intersection of the two curves projected on the α axle determines the value of α. Then graphically the degree of risk could be obtained as has been mentioned above.

By plotting the values of the relative weighted values w_1/w_2, the minimum weighting ratio R_{min} for each curve and the coefficient of risk ρ for each curve in relation to α (Fig 4.9), the range of preference can be made. The coefficient of risk aversion of each function is:

F gives a coefficient risk of -0.46
E gives a coefficient risk of -0.62
H_o gives a coefficient risk of -0.69

F is preferred to E and H_o because it has a lower modulus coefficient of risk. A particular value of α can determine graphically the corresponding values of w_1/w_2, ρ and R_{min} for F (Fig 4.8).

α	ρ	$\frac{w_1}{w_2}$	R_{min}
0	-1	∞	-
0.1	-0.8	81	28.88
0.2	-0.6	16	7.82
0.3	-0.4	5.44	8.22
0.4	-0.2	2.25	24.11

At α = 0.2 and the modulus of the coefficient of risk ρ greater than 0.6, the cumulative probability function will be preferred to G because the relative weights w_1/w_2 are greater than the minimum weight ratio R_{min}. For any given value of α in [0;0.5], the exact value of the degree of risk aversion ρ can be determined graphically in Figure 4.9.

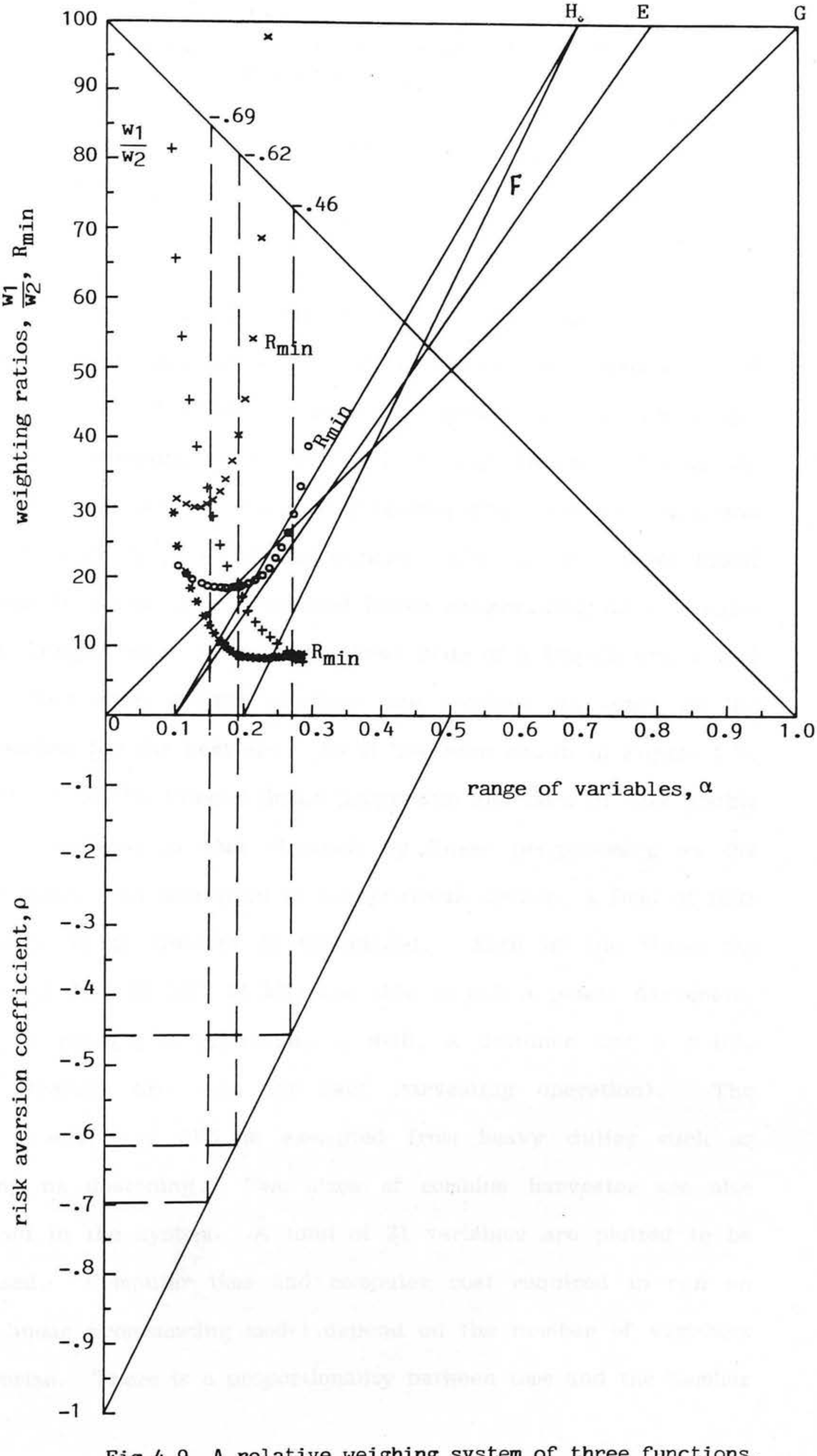

Fig 4.9 A relative weighing system of three functions, E, F, H_o

Example: at $\alpha = 0.27$ the cumulative function F has a degree of risk aversion $\rho = -0.46$

at $\alpha = 0.18$ the cumulative function E has a degree of risk aversion $\rho = -0.62$

at $\alpha = 0.15$ the cumulative function H_o has a degree of risk aversion $\rho = -0.69$

4.3 Optimum solution by integer linear programming

The objective of this section is to select the most efficient and economical machine (excluding tractor and labour costs at this stage) to perform a cropping system with a four crop rotation. To satisfy this objective, an integer linear programming model was developed and used in this study. A starting solution value of the integer linear programme is given by conventional linear programming as a feasible and non integer value which is the first node of a branch and bound method, then some integer solutions are obtained en route as the model reaches for the best one. As it has been shown in Figure 4.2, the solutions of the integer linear programme are more or less double in value compared to that obtained by linear programming as the starting point. As mentioned in the previous section, a fleet of four different sizes of tractors is considered. Each of the three big tractors (61 kW, 74 kW, 94 kW) are able to pull a potato harvester, trailers, a plough, a cultivator, a drill, a destoner and a potato planter (trailers are used for each harvesting operation). The smallest tractor (45 kW) is exempted from heavy duties such as ploughing or destoning. Two sizes of combine harvester are also considered in the system. A total of 31 variables are plotted to be integerised. Computer time and computer cost required to run an integer linear programming model depend on the number of variables to integerise. There is a proportionality between time and the number of variables. The higher the number of variables, the more time is needed to solve the problem and the higher will be the cost. In this case, an overnight detached program run does not produce a feasible integer solution. This means that the number of combinations of variables to integerise at the same time is enormously large. There are two ways of reducing the number of variables without reducing the activities of the different crop operations throughout the year. These arise since the year is divided into different periods in which different operations occur. It appears that the peak workload occurs in the period where harvesting winter wheat and lifting potatoes have to be done in a short time before getting to the optimum date of sowing winter wheat (14-23 October) for next year. In that period, the most deterministic operation is potato harvesting which requires at least three tractors per harvester to perform the task. The question arising is whether the number of tractors determined in that peak workload period will be sufficient to cover all the rest of the operations of the whole year. By using this method, the number of variables to integerise is decreased to half or less because all the sizes of tractors will not be involved in carrying out the task, one or two sizes will be enough, the others becoming redundant in the model. The reduced group of variables becomes one variable to represent a potato harvester, two for trailers (for the plough and the destoner one or two depending on whether or not a 45 kW tractor is selected), two for the cultivator, two for the drill, two for the potato planter and two for the two sizes of combine harvester considered. The total number reaches 13 if the 45 kW tractor is chosen or 15 if another size of tractor is involved. Each variable represents a single piece of equipment and the number is determined depending on the size and number of pieces of equipment selected by the model. A tractor cannot be included with each piece of trailed equipment because it can be depreciated only once. Therefore the tractor number can be added at the final costing procedure. This method can be illustrated by one example shown in Table 4.11 in which the first solution which is the optimum contains two potato harvesters, two small combine harvesters, four trailers, three ploughs, a big and a small drill, a small cultivator, a small planter, and a destoner; the number of tractors required for this example will be six tractors, three of 61 kW and three of 45 kW. The 61 kW tractors will be used for potato lifting, ploughing, drilling and destoning, and some of them for transport during harvesting operations; 45 kW tractors will be used for cultivating, drilling, planting and transport. Alternatively, the number of tractors to be owned can be reduced to three of 61 kW and one of 45 kW, but the two of 45 kW can be hired during the harvesting season. The exercise of running the model has been repeated for different sizes of farm in order to determine the effect of machinery selection with several alternative integer solutions using two sizes of tractors. Several runs of the model were carried out to reach integer solutions. The running time was still high depending on the number of iterations created from the first feasible and non integer solution to find the first integer solution and the number of non-solved problems in branches remaining to be analysed, with a value less than that of the integer solution obtained. The higher the number, the more time is needed to solve the problem of getting better solutions. The results of five different farm sizes (100 ha, 150 ha, 200 ha, 250 ha, and 300 ha) using a 45 kW and a 61 kW tractor size are presented in Tables 4.8, 4.9, 4.10, 4.11 and 4.12. The

Table 4.8 Sets of machines for a 100 ha farm using 45 kW and 61 kW tractors

Power source (kW)	45			61						Self Prop Combine harv		Transport		Costs
Operations	Cult	Drill	Plant	Plough	Cult	Drill	Destone	Plant	Pot harv					
Rate of work(ha/h)	1.9	1.5	0.3	0.62	2.4	1.9	0.4	0.4	0.3	1.3	1.55			(£k)
	1	1	1	2	0	0	1	0	1	1	0	1	1	33.20
	1	1	0	2	0	0	1	1	1	1	0	1	1	33.40
	1	0	1	2	0	1	1	0	1	1	0	1	1	33.50
	0	1	1	2	1	0	1	0	1	1	0	1	1	33.50
	0	1	0	2	1	0	1	1	1	1	0	1	1	33.70
	1	0	0	2	0	1	1	1	1	1	0	1	1	33.70
	0	0	1	2	1	1	1	0	1	1	0	1	1	33.80
	0	0	0	2	1	1	1	1	1	1	0	1	1	34.00
	1	1	1	2	0	0	1	0	1	0	1	1	1	34.20
	1	0	1	2	0	1	1	0	1	0	1	1	1	34.50
	0	1	1	2	1	0	1	0	1	0	1	1	1	34.50
	1	0	0	2	0	1	1	1	1	0	1	1	1	34.70
	0	0	1	2	1	1	1	0	1	0	1	1	1	34.80
	0	0	0	2	1	1	1	1	1	0	1	1	1	35.00

Table 4.9 Sets of machines for a 150 ha farm using 45 kW and 61 kW tractors

Power source (kW)	45			61						Self Prop Combine harv		Transport		Costs
Operations	Cult	Drill	Plant	Plough	Cult	Drill	Destone	Plant	Pot harv					
Rate of work(ha/h)	1.9	1.5	0.3	0.62	2.4	1.9	0.4	0.4	0.3	1.3	1.55			(£k)
	1	0	1	2	0	1	1	0	1	1	0	1	1	33.50
	1	0	0	2	0	1	1	1	1	1	0	1	1	33.70
	0	0	1	2	1	1	1	0	1	1	0	1	1	33.80
	0	0	0	2	1	1	1	1	1	1	0	1	1	34.00
	1	0	1	2	0	1	1	0	1	0	1	1	1	34.50
	1	0	0	2	0	1	1	1	1	0	1	1	1	34.70
	0	0	1	2	1	1	1	0	1	0	1	1	1	34.80
	0	0	0	2	1	1	1	1	1	0	1	1	1	35.00

Table 4.10 Sets of machines for a 200 ha farm using 45 kW and 61 kW tractors

Power source (kW)	45			61						Self Prop				Costs
Operations	Cult	Drill	Plant	Plough	Cult	Drill	Destone	Plant	Pot harv	Combine harv		Transport		
Rate of work(ha/h)	1.9	1.5	0.3	0.62	2.4	1.9	0.4	0.4	0.3	1.3	1.55			(£k)
	1	2	1	3	0	0	1	0	2	0	1	2	2	47.50
	1	2	0	3	0	0	1	1	2	0	1	2	2	47.70
	0	2	1	3	1	0	1	0	2	0	1	2	2	47.80
	1	1	1	3	0	1	1	0	2	0	1	2	2	47.80
	1	1	0	3	0	1	1	1	2	0	1	2	2	48.00
	0	2	0	3	1	0	1	1	2	0	1	2	2	48.00
	1	0	1	3	0	2	1	0	2	0	1	2	2	48.10
	0	1	1	3	1	1	1	0	2	0	1	2	2	48.10
	0	1	0	3	1	1	1	1	2	0	1	2	2	48.30
	1	0	0	3	0	2	1	1	2	0	1	2	2	48.30
	0	0	1	3	1	2	1	0	2	0	1	2	2	48.40
	0	0	0	3	1	2	1	1	2	0	1	2	2	48.60

Table 4.11 Sets of machines for a 250 ha farm using 45 kW and 61 kW tractors

Power source (kW)	45			61						Self Prop Combine harv		Transport		Costs
Operations	Cult	Drill	Plant	Plough	Cult	Drill	Destone	Plant	Pot harv					
Rate of work(ha/h)	1.9	1.5	0.3	0.62	2.4	1.9	0.4	0.4	0.3	1.3	1.55			(£k)
	1	1	1	3	0	1	1	0	2	2	0	2	2	52.80
	1	1	0	3	0	1	1	1	2	2	0	2	2	53.00
	1	0	1	3	0	2	1	0	2	2	0	2	2	53.10
	0	1	1	3	1	1	1	0	2	2	0	2	2	53.10
	0	1	0	3	1	1	1	1	2	2	0	2	2	53.30
	1	0	0	3	0	2	1	1	2	2	0	2	2	53.30
	0	0	1	3	1	2	1	0	2	2	0	2	2	53.40
	0	0	0	3	1	2	1	1	2	2	0	2	2	53.60
	1	1	1	3	0	1	1	0	2	1	1	2	2	53.80
	1	0	1	3	0	2	1	0	2	1	1	2	2	54.10
	0	1	1	3	1	1	1	0	2	1	1	2	2	54.10
	0	0	0	3	1	2	1	1	2	1	1	2	2	54.60

Table 4.12 Sets of machines for a 300 ha farm using 45 kW and 61 kW tractors

Power source (kW)	45			61						Self Prop				Costs
Operations	Cult	Drill	Plant	Plough	Cult	Drill	Destone	Plant	Pot harv	Combine harv		Transport		
Rate of work(ha/h)	1.9	1.5	0.3	0.62	2.4	1.9	0.4	0.4	0.3	1.3	1.55			(£k)
	1	0	1	4	0	2	1	0	2	2	0	2	2	55.90
	0	0	1	4	1	2	1	0	2	2	0	2	2	56.20
	0	0	0	4	1	2	1	1	2	2	0	2	2	56.40
	0	0	0	4	1	2	1	1	2	1	1	2	2	57.40

optimum capacity of machines was chosen in each case with several alternative integer solutions. The solutions are very close in terms of cost. A sensitivity analysis could be applied to distinguish between solutions. The difference between solutions for the same farm size appears to arise because of changing one size of implement; for example changing the size of the drill gives two different integer solutions (Table 4.8). With the 100 ha farm size, all solutions contain the same size of potato harvester, destoner, plough and trailers. The difference is shown by substituting one implement by a bigger or a smaller one for cultivating, sowing, planting or combine harvesting. The combination of the changes gives several solutions to the problem. As the farm size increases to 150 ha (Table 4.9) the number of solutions is reduced compared to the 100 ha farm size. The solutions obtained are selected from that for 100 ha using a big drill. The small drill is not sufficient for the 150 ha area. The rest of the implements remained unchanged. The conclusion is therefore that some of the solutions selected for 100 ha can also efficiently satisfy a 150 ha farm size. For a 200 farm size (Table 4.10) the number of ploughs increases from two to three, potato harvesters become two, trailers four, drills two and combine harvesting can be done only with the large harvester size (1.55 ha/h). There is no relationship between the 150 ha and 200 ha farm size in terms of cost since most of the equipment sizes are increased. For the 250 ha farm size (Table 4.11), most of the equipment used in the 200 ha farm to establish the crop is used but the only difference arises in harvesting; one combine harvester is not enough, so two combine harvesters are selected. A similar relationship arose between the 100 ha and 150 ha farm sizes in terms of cost. For the 300 ha farm size (Table 4.12), the number of solutions is reduced due to the increase in the number of ploughs and the selection of two big drills. There is a feasible relationship between a 250 ha and 300 ha farm size. The conclusion drawn is that the increase in power must follow the increase in area because at 300 ha, four tractors of 61 kW used to plough could be replaced by two tractors of 61 kW and one tractor of 74 kW or one tractor of 61 kW and two of 74 kW which would reduce the annual cost, fuel cost and labour cost.

The second method of reducing the number of variables to be integerised is to combine all the equipment matched with a tractor plus a potato harvester into a set. A set contains a plough, cultivator, drill, destoner, planter and potato harvester. Trailers are discarded from the set because they could not be trailed at the same time as when the tractor is pulling the potato harvester. A tractor can perform only one job within a set. The total number of variables to integerise is four for different sets (45 kW, 61 kW, 74 kW and 94 kW), two for combine harvesters and two for trailers. The computer time and cost is much lower to solve an integer linear programming problem using the machinery sets method than integerising each single machine and item of equipment needed in the model. The same scenario is repeated with different sizes of farm as has been done with the integerisation of individual items of equipment. The results of several computer runs are shown in the following Tables (4.13; 4.14; 4.15; 4.16; 4.17). The first set with a 45 kW tractor size has not been selected in all cases because the set is incomplete; it does not contain a potato harvester, a plough, or a destoner. It has been mentioned before that a 45 kW tractor cannot handle heavy duties. A lower rate of work and the length of the period are the two

Table 4.13 A 100 ha farm using sets method

Sets	S_1	S_2	S_3	S_4	C_1	C_2			Costs	Net cost
Power source (kW)	45	61	74	94	Self prop.		Transport		(£k)	(£k) *
	0	0	1	0	1	0	1	1	33.00	-
	0	0	0	1	1	0	1	1	33.80	-
	0	0	1	0	0	1	1	1	34.00	-
	0	0	0	1	0	1	1	1	34.80	-
	0	2	0	0	1	0	1	1	53.40	34.00
	0	2	0	0	0	1	1	1	54.40	35.00

* excluding the cost of redundant machines in multiple sets

Table 4.14 A 150 ha farm using sets method

Sets	S_1	S_2	S_3	S_4	C_1	C_2			Costs
Power source (kW)	45	61	74	94	Self prop.		Transport		(£k)
	0	2	0	0	1	0	1	1	53.40
	0	2	0	0	0	1	1	1	54.40
	0	1	1	0	1	0	1	1	55.20
	0	1	0	1	1	0	1	1	56.00
	0	1	1	0	0	1	1	1	56.20
	0	1	0	1	0	1	1	1	57.00
	0	0	2	0	1	0	1	1	57.00
	0	0	1	1	1	0	1	1	57.80
	0	0	2	0	0	1	1	1	58.00
	0	0	0	2	1	0	1	1	58.60
	0	0	1	1	0	1	1	1	58.80
	0	0	0	2	0	1	1	1	59.60

Table 4.15 A 200 ha farm using sets method

Sets	S_1	S_2	S_3	S_4	C_1	C_2			Costs
Power source (kW)	45	61	74	94	Self prop.		Transport		(£k)
	0	1	1	0	0	1	2	2	59.30
	0	1	0	1	0	1	2	2	60.10
	0	0	2	0	0	1	2	2	61.10
	0	0	1	1	0	1	2	2	61.90
	0	0	0	2	0	1	2	2	62.70
	0	1	1	0	2	0	2	2	64.30
	0	1	0	1	2	0	2	2	65.10
	0	0	2	0	2	0	2	2	66.10
	0	0	1	1	2	0	2	2	66.90
	0	0	0	2	2	0	2	2	67.70
	0	3	0	0	0	1	2	2	69.70

Table 4.16 A 250 ha farm using sets method

Sets	S_1	S_2	S_3	S_4	C_1	C_2			Costs
Power source (kW)	45	61	74	94	Self prop.		Transport		(£k)
	0	0	2	0	2	0	2	2	66.10
	0	0	1	1	2	0	2	2	66.90
	0	0	2	0	1	1	2	2	67.10
	0	0	0	2	2	0	2	2	67.70
	0	0	1	1	1	1	2	2	67.90
	0	0	0	2	1	1	2	2	68.70
	0	0	1	1	0	2	2	2	68.90
	0	0	0	2	0	2	2	2	69.70

Table 4.17 A 300 ha farm using sets method

Sets	S_1	S_2	S_3	S_4	C_1	C_2			Costs
Power source (kW)	45	61	74	94	Self prop.		Transport		(£k)
	0	2	1	0	2	0	2	2	86.40
	0	2	0	1	2	0	2	2	87.20
	0	2	1	0	1	1	2	2	87.40
	0	2	0	1	1	1	2	2	88.20
	0	1	2	0	2	0	2	2	88.20
	0	2	1	0	0	2	2	2	88.40
	0	1	1	1	2	0	2	2	89.00
	0	2	0	1	0	2	2	2	89.20
	0	1	2	0	1	1	2	2	89.20
	0	1	0	2	2	0	2	2	89.80
	0	1	1	1	2	0	2	2	90.00
	0	0	3	0	2	0	2	2	90.00
	0	1	2	0	0	2	2	2	90.20
	0	1	0	2	1	1	2	2	90.80
	0	0	2	1	2	0	2	2	90.80
	0	1	1	1	0	2	2	2	91.00
	0	0	3	0	1	1	2	2	91.00
	0	0	1	2	2	0	2	2	91.60
	0	0	2	1	1	1	2	2	91.80
	0	1	0	2	0	2	2	2	91.80
	0	0	3	0	0	2	2	2	92.00
	0	0	0	3	2	0	2	2	92.40
	0	0	1	2	1	1	2	2	92.60
	0	0	2	1	0	2	2	2	92.80
	0	0	0	3	1	1	2	2	93.40
	0	0	1	2	0	2	2	2	93.60
	0	0	0	3	0	2	2	2	94.40
	0	4	0	0	2	0	2	2	106.80
	0	4	0	0	1	1	2	2	107.80

parameters which characterise the selection and the number of sets. Since the lowest rate of work in the model is given by the potato harvester and the plough, the set matched with a 45 kW tractor can never be used. As the area of a farm increases from 100 ha to 300 ha, sets are increasing in size and number in two dimensions.

For the 100 ha farm size one set of machines with a 74 kW tractor is the optimum solution (Table 4.13). The job could also be performed by two sets of machines with a 61 kW tractor. On the other hand, the optimum solution obtained for the same size of farm by using the individual equipment integerisation method is two tractors of 61 kW to perform the ploughing task and one tractor of 45 kW to cultivate and plant (Table 4.8). However, an alternative solution with a value of £34000 in the same table (4.8) can be selected with only two tractors of 61 kW. The difference between this alternative solution and the optimum is £800. In terms of equipment selection, the optimum solution gives the correct matching of equipment, but in terms of the number of tractors selected, the alternative solution with two 61 kW tractors is much better than the optimum since it saves a tractor of 45 kW and a driver. Two 61 kW tractors are found to be a solution by using the "set of equipment" integerisation method but not as an optimum (Table 4.13). The different costs of what may appear to be the same solution from the different methods arises for the following reason: in the "individual equipment" integerisation method the second tractor of 61 kW is used only for ploughing, so there are two ploughs but only one each of cultivator, drill, planter, destoner and potato harvester; however, the "sets of equipment" integerisation method assumes that there are two of every item of equipment, so the total cost is higher. By deducting the cost of the redundant machines, the net cost by means of the "sets of equipment" integerisation method is identical with the cost obtained by the "individual equipment" integerisation method. There is however a very large reduction in computing time by using the "sets of equipment" integerisation method. By using this latter method, for example, computing time of 350s is required for 100 ha farm compared with 650s using the "individual equipment" integerisation method to get a partial solution. It has been mentioned before that even with an overnight detached program run, a feasible solution using the "individual equipment integerisation method" cannot be obtained for machines matched with the four sizes of tractor considered in this study.

For the 150 ha farm size, a combination of two tractor sizes is found between the three sets, e.g. two tractors of 61 kW, one 61 kW and one 74 kW,; one 61 kW and one 94 kW; one 74 kW and one 94 kW; two 74 kW or two 94 kW to perform the task (Table 4.14). With this size of farm, two 61 kW tractors become the optimum solution which is not the case when using the individual equipment integerisation method (Table 4.9). The fact that two 61 kW tractors are acceptable for a 150 ha farm size indicates that they were inefficiently used on a 100 ha farm size, the smaller farm being overpowered.

For the 200 ha farm size, the demand for sets is the same except for that based on a 61 kW tractor where three are needed to do the task (Table 4.15). For the 250 ha farm size, some solutions used for the 200 ha farm size with two combine harvesters only, are selected because one combine harvester cannot complete the job in the available time. It is a question of efficiency. A solution with three tractors of

61 kW has not been selected because it has been achieved with only one combine harvester. The set matching a 61 kW tractor has not been selected at all (Table 4.16). For the 300 ha farm size, there is a double combination between three sets and two sizes of combine harvesters. Three sets of different sizes or four sets of 61 kW tractors and two combine harvesters are required to complete the job.

The feasible solutions for a 250 ha farm size obtained by a conventional linear programming model are given in Tables 4.18a and 4.18b respectively, using the individual variable for each item of equipment matched with 45 kW and 61 kW tractors and the sets method. Comparing the solution from Table 4.18a with the solutions obtained in Table 4.11, there is a large difference in terms of cost. A difference of £21000 in the optimum solution and £22600 in the last solution is shown. If the solution of the linear programme in Table 4.18a is rounded to the next integer variable, the result of the solution becomes two ploughs, one cultivator, two drills, one destoner, one planter, two potato harvesters with four trailers, and one or two large combine harvesters. There is no such solution obtained in Table 4.11 with one or two large combine harvesters. If one small and one large combine harvester are considered, the last solution of Table 4.11 is obtained with the highest cost. Comparing the solution from Table 4.18b with the solutions obtained in Table 4.16, the difference in terms of cost is £11600 compared with the optimum solution and £15200 compared with the last solution. If the solution for non integer variables is rounded to the next integer variable as has been done in the previous case, the solution of Table 4.18b becomes two sets of 94 kW tractors, one or two large combine harvesters and four trailers. Also there is no solution obtained in

Table 4.18 A 250 ha farm using conventional linear programming method

a. Individual equipment method

Power source (kW)	45			61						Self Prop				Costs
Operations	Cult	Drill	Plant	Plough	Cult	Drill	Destone	Plant	Pot harv	Combine harv		Transport		
Rate of work(ha/h)	1.9	1.5	0.3	0.62	2.4	1.9	0.4	0.4	0.3	1.3	1.55			(£k)
	0	0	0	2.52	0.65	1.64	0.47	0.47	1.59	0	1.08	1.59	1:59	38.02

b. Set method

Sets	S_1	S_2	S_3	S_4	C_1	C_2			Costs
Power source (kW)	45	61	74	94	Self prop.		Transport		(£k)
	0	0	0	1.70	0	1.08	1.59	1.59	54.50

Table 4.16 with one large combine harvester. All the solutions are obtained with a combination of two combine harvesters. Three solutions could be similar to the result if two combine harvesters are considered, with the values of £67700, £68700 and £69700.

Hence the integerisation of a problem cannot be achieved by rounding a solution obtained by a linear programming model or just by guessing. The results of the solutions in different cases show that there is no relation between the solution obtained by a linear programming model and the optimum solution obtained by the integerisation method using the branch and bounding system. The algorithm of the integerisation method should be used to save power, labour, fuel and to invest properly.

It will be more acceptable for a manager or farmer to have an optimum solution by integerising each single item of equipment or machine for an existing fleet size of tractors, because the solution obtained for the machinery to be used is a function of the existing tractor sizes. However using the method of sets optimises the number of tractors and men in the system. The model selects the whole range of equipment within a set as one variable which includes some equipment which could not be used or utilised efficiently, because the set has been selected many times for a given period or the equipment is too large for a given area. Using a single machine gives the right size of machine to perform the task. The solution of the sets method is analysed through the interpreter which is the last phase of the program. In each activity, the number of available hours is balanced with the number of required hours. If the required hours are less than the available hours, the difference is taken as a slack, but if the opposite happens, the number of selected sets increases which increases the available hours. The equality equation between the supplied and required hours is created by penalising all the activities in the objective row of the matrix by a negligible value. The analysis of the interpreter has to be done step by step to determine the number of hours required and available in each activity. The number of sets selected is given. From this information, the exact machinery used can be determined.

The purpose of this section is to demonstrate the possible utility of integer linear programming as an extension tool for farmers and managers for adjusting an existing machinery complement or to optimise a new set for a given farm size. For less than 10% of good weather (greater than 90% probability level), the number of available work days decreases, therefore two sets of machinery are not sufficient to perform the task on time. The results of the integer linear programming using the sets method at 90% probability level are given in Table 4.19. The number of sets needed at that level is four for all the solutions selected instead of two with a 75% probability level.

Linear programming model is not a suitable vehicle for studying the effect of risk because the cut-off point at the tail of the available days relationship is subject to significant errors. The results of an integer solution could be output information to complement research further by using other mathematical algorithms.

Table 4.19 A 250 ha farm size using set method at 90% probability level

Sets	S_1	S_2	S_3	S_4	C_1	C_2			Costs
Power source (kW)	45	61	74	94	Self prop.		Transport		(£k)
		1	2	1	2	0	4	4	119.15
		0	1	2	2	0	4	4	119.95
		0	4	0	2	0	4	4	120.15
		1	0	3	2	0	4	4	120.75
		1	1	2	1	1	4	4	120.94
		0	3	1	2	0	4	4	120.94
		0	4	0	1	1	4	4	121.15
		0	2	2	2	0	4	4	121.75
		1	0	3	1	1	4	4	121.75
		0	3	1	1	1	4	4	121.94
		1	1	2	0	2	4	4	121.94
		0	1	3	2	0	4	4	122.55
		0	2	2	1	1	4	4	122.75
		1	0	3	0	2	4	4	122.75
		0	3	1	0	2	4	4	122.94
		0	0	4	2	0	4	4	123.35
		0	1	3	1	1	4	4	123.54
		0	2	2	0	2	4	4	123.74
		0	0	4	1	1	4	4	124.34
		0	1	3	0	2	4	4	124.54
		0	0	4	0	2	4	4	125.34

4.4 Simulation analysis

A 250 hectare arable farm with a rotation of potatoes, winter wheat, spring barley, and winter barley was chosen using the integer linear programming model to determine the number of sets sufficient to perform the task of different operations during the year. The job consists of the establishment of the crops, harvesting and transport. The results of integer linear programming using the integerisation sets method are given in Table 4.16. These results are analysed by the interpreter LP87PR which is the third part of the integer linear programming model (Appendix C3). In each integer solution, the interpreter determines the items of equipment used within the sets selected in the solution and the number of hours required for each operation. The redundant items are discarded from the analysis. The different items of equipment used in each solution are given in detail with their corresponding rate of work in Table 4.20. Each solution has a unique symbol to identify it. From the solutions in Table 4.20, the number of tractors used for the 250 ha farm size could be predicted to be six tractors during the potato harvesting period because two potato harvesters are selected in all the solutions. Two big tractors are used to pull the harvesters and four small tractors (45 kW) for the potato transport. Ownership of the tractors could be tackled in three ways. Firstly, owning all the tractors; secondly, owning four and hiring two small ones during the potato harvesting period; and thirdly, hiring all the tractors. The case considered in this study is to own four tractors, two selected in the solutions (two 74 kW, or one 74 kW and one 94 kW or two 94 kW) plus two 45 kW for cereal and potato harvest transport; in addition, the last two could be hired to perform the potato harvesting. The

Table 4.20 Different items of equipment used in different solutions for a 250 ha farm using sets method

Sets No.	Symbol	74 kW tractor						94 kW tractor						Self Prop.		Trailers	
		Plough	Cult.	Drill	De-stone	Plant-er	Pot Harv.	Plough	Cult.	Drill	De-stone	Plant-er	Pot Harv.	C_1	C_2		
Rate of work		0.8	3.2	2.5	0.5	0.6	0.3	0.92	4.8	3.8	0.6	0.6	0.3	1.3	1.55		
1	▽	0	0	0	0	0	0	2	1	1	1	1	2	2	0	2	2
2	o	0	0	0	0	0	0	0	2	1	1	1	2	1	1	2	2
3	*	0	0	0	0	0	0	2	1	1	1	1	2	0	2	2	2
4	□	1	0	0	0	0	1	1	1	1	1	1	1	2	0	2	2
5	+	2	1	2	1	1	2	0	0	0	0	0	0	2	0	2	2
6	x	1	0	0	0	0	1	1	1	1	1	1	1	1	1	2	2
7	△	1	0	0	0	0	1	1	1	1	1	1	1	0	2	2	2
8	◇	2	1	2	1	1	2	0	0	0	0	0	0	1	1	2	2

annual number of hours used by each tractor is determined by adding the annual number of hours required for each item of equipment in a a set used with the tractor in all its different operations. A further 200 hours are added to the total annual number of hours for each tractor owned for miscellaneous work such as spreading manure, baling etc which are not considered in this study. An example of calculation of number of hours of use per year for each tractor is given in Table 4.21.

The expected field performance of each selected solution in Table 4.20 is simulated throughout the sequence of available work days. By using a process built into the simulation for each period of the year, a simulation of 100 cycles is carried out for each solution. The solutions for basic sets of tillage machines consist of two ploughs, one cultivator, one or two drills, one destoner and one planter. The difference between solutions consists mainly of the variation of the combine harvester size, the drill size and the destoner size with each set of tillage machines selected. The results show the importance of combine harvester and destoner capacity in establishing the ranking order of the gross revenue (Table 4.22). All solutions are plotted in Figures 4.10, 4.11 and 4.12 to demonstrate the variation in size of items of equipment used in each solution. Solutions 1, 2 and 3 of Table 4.20 are represented in Figure 4.10; solutions 1, 4 and 5 are represented in Figure 4.11 and solutions 6, 7 and 8 are represented in Figure 4.12. In Figure 4.10 the items of equipment used for establishment are the same, the variation between the solutions arises because of the different sizes of combine harvester. The three solutions select two combine harvesters with different sizes. Figure 4.10 shows that the two combine harvesters selected each with a rate

Table 4.21 Annual hours of use of each selected tractor in the farm

Tractor number	1	2	3	4	5*	6*
Power (kW)	94	94	45	45	45	45
<u>Activities</u>:						
Ploughing	118	118	-	-	-	-
Cultivating	52	-	-	-	-	-
Drilling	53	-	-	-	-	-
Destoning	84	-	-	-	-	-
Planting	84	-	-	-	-	-
Cereal transport	77	77	77	77	-	-
Potato transport	84	84	84	84	84	84
Miscellaneous	200	200	200	200	-	-
Total	752	479	361	361	84	84

* Tractors 5 and 6 are hired

Table 4.22 Dominance ranking order on gross revenue

mean	295.73	295.68	295.57	295.54	295.07	295.11	294.07	293.4
standard deviation	3.26	3.36	3.38	3.49	3.788	3.793	6.03	6.33
solution number	3	7	2	6	4	1	8	5
ranking order	1	2	3	4	5	6	7	8
symbols	*	△	o	x	□	▽	◇	+

Table 4.23 Dominance ranking order on net revenue of selected solutions

mean	248.52	251.18	250.06	251.05
solution number	3	1	8	5
first ranking order	1	2	3	4
second ranking order	4	1	3	2
symbols	*	▽	◇	+

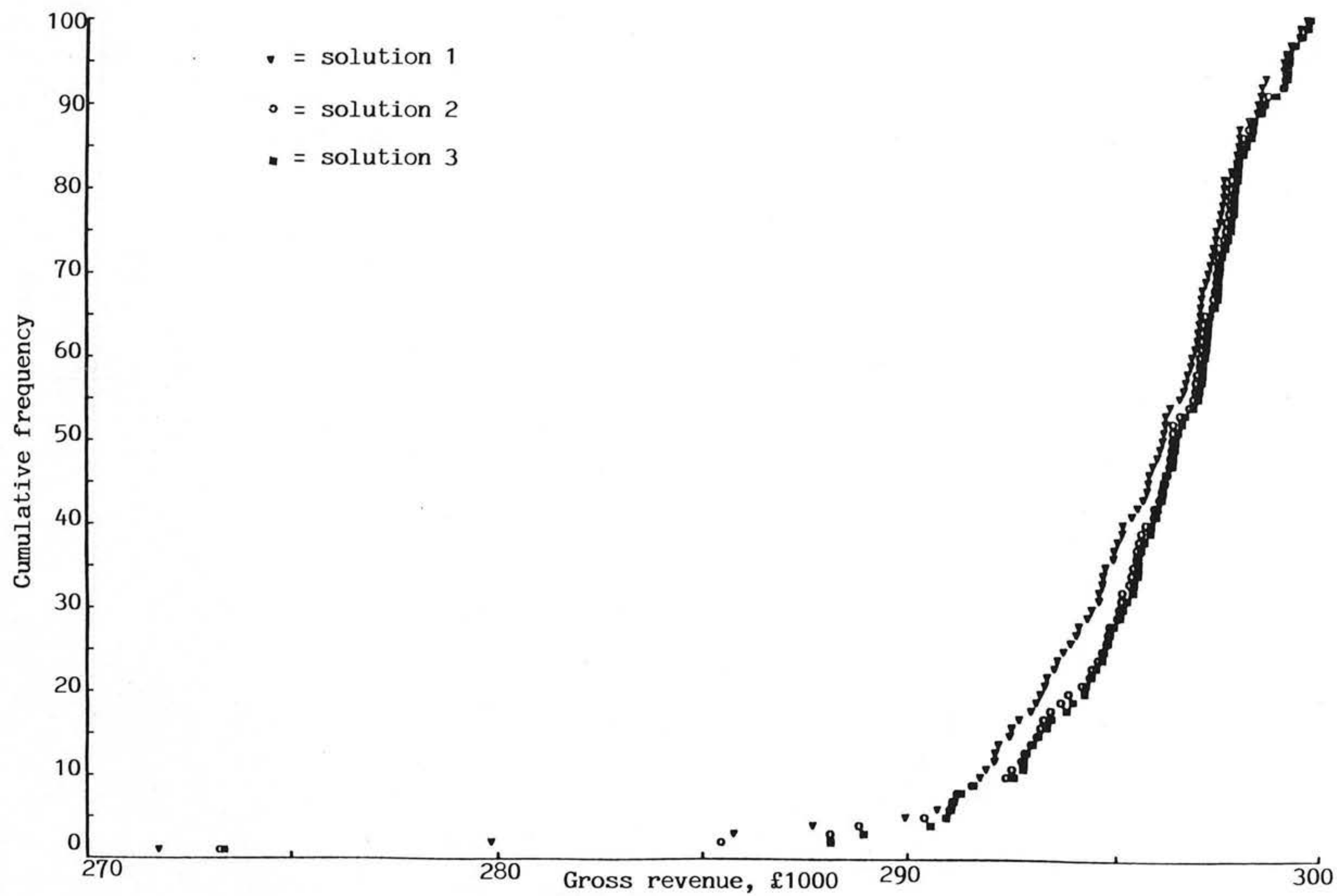

Fig 4.10 First order stochastic dominance using different sizes of combine harvester but same size of establishment items of equipment

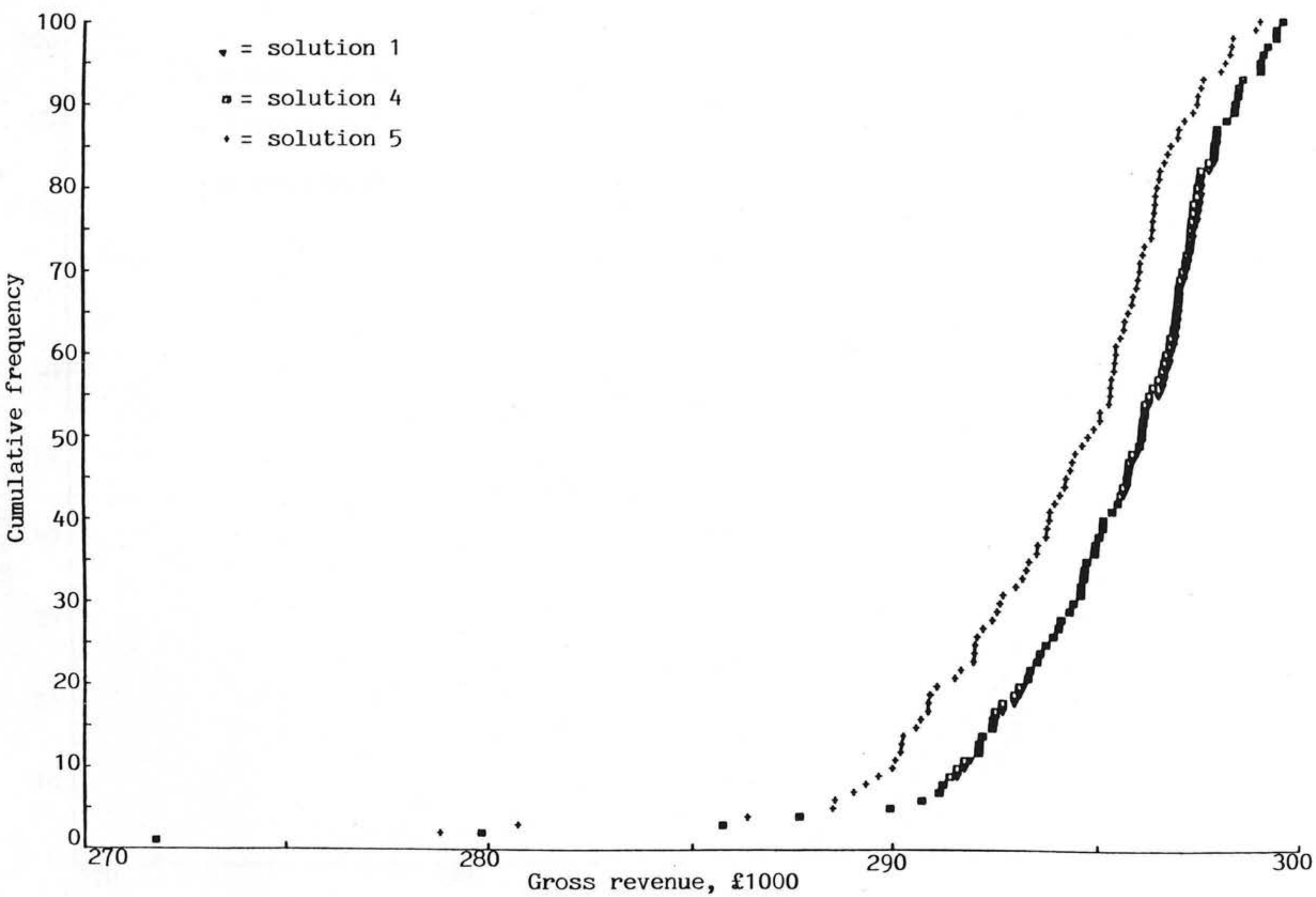

Fig 4.11 First order stochastic dominance, using same size of combine harvester but different establishment items of equipment

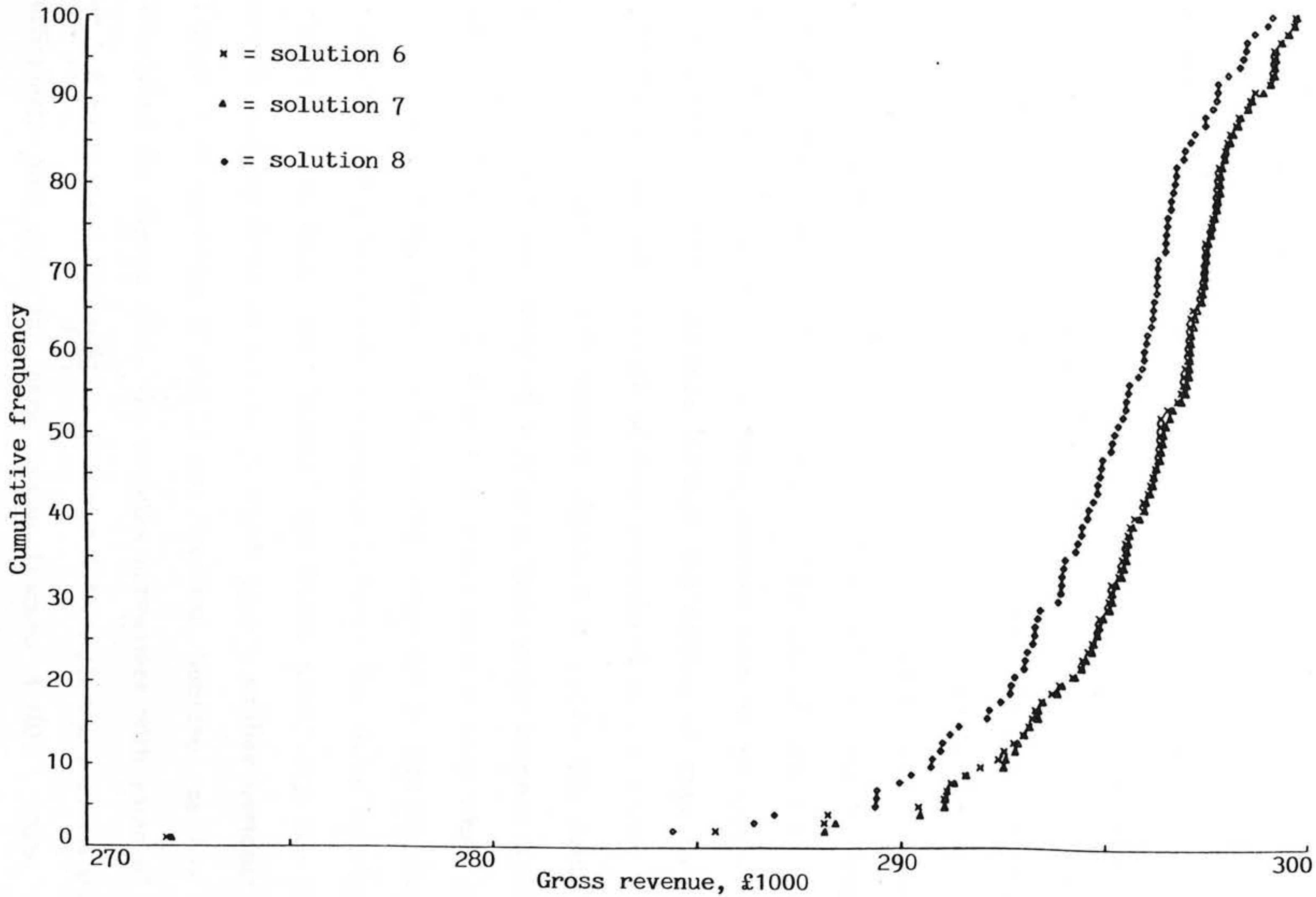

Fig 4.12 First order stochastic dominance using different sizes of combine harvesters and different establishment items of equipment

of work of 1.3 ha/h, give less income than the other two solutions which are almost identical. The rate of work used for solutions 2 and 3 are respectively 1.3 ha/h, 1.55 ha/h and 1.55 ha/h for each combine harvester. The variation in terms of gross income is small because losses arise only due to the variation of the rate of work during cereal harvesting. In Figure 4.11 the combine harvester sizes are constant, but the items of equipment for establishment differ. Solution 5 is completely different from solutions 1 and 4. The items of equipment used in solution 5 are in two sets matched with two tractors of 74 kW but solution 1 uses two sets of two tractors of 94 kW and solution 4 uses one set with a 74 kW tractor and one set with a 94 kW tractor. Solution 5 differs from the other two by way of a second drill and a smaller destoner. The use of one drill matched with a 94 kW tractor or two drills matched with 74 kW tractors does not affect the gross revenue because the number of days needed to perform the job for the size of farm considered in this study is more or less the same in both cases. Figure 4.11 shows that solutions 1 and 4 are identical. Solution 5 gives a lower gross revenue because a smaller destoner with a rate of work of 0.5 ha/h is used which delays the potato planting date, and hence the losses due to late planting are higher. The gross revenue variation between the three solutions in Figure 4.11 is again small because the losses arise only due to the potato planting delay in solution 5 which uses a smaller destoner. In Figure 4.12 solutions 6 and 7 are identical because, as has been mentioned for Figure 4.10, the combine harvesters with rates of work of 1.3 ha/h and 1.55 ha/h, or two with 1.55 ha/h can perform the job efficiently and give the same curve (Figure 4.10). Then it is assumed that the combine harvester sizes are constant. Solution 8 gives a lower gross revenue because the same scenerio is repeated as in Figure 4.11. The small destoner is used in solution 8 which again delays the potato planting. After discarding the similar solutions from Figures 4.10, 4.11 and 4.12, solutions 1, 3, 5 amd 8 are selected and plotted in Figure 4.13 to show the ranking order in terms of the gross revenue between the different solutions obtained by the integer linear programming method. The limitation value of the four machine sets selected in Figure 4.13 could achieve £300,000 in gross revenue. The same upper limit of £299,000 is almost attained by all machinery sets in very good weather. The results are negatively skewed which makes stochastic dominance ranking of the gross revenue easy. The ranking order on the basis of gross revenue is expected to show the largest machinery set to be dominant with the greatest mean and smallest variance. Table 4.22 shows that solution 3 selected with two 94 kW tractors, two ploughs, one cultivator, one drill, one destoner, one planter, two potato harvesters and two big combine harvesters gives the highest income with the greatest mean and lowest standard deviation; solution 5 selected with two 74 kW tractors, two ploughs, one cultivator, two drills, one destoner, one planter, two potato harvesters and two small combine harvesters gives the lowest income with the lowest mean and highest standard deviation. The negative skewing is around two to three thousand pounds because there is not a big difference between the selected solutions.

After deducting the fuel and annual costs of each item of equipment used in the selected solutions in Figure 4.13, the second order criteria of stochastic dominance is invoked because the cumulative distribution functions cross. The second order of stochastic dominance is used to help to identify the preferred solution for risk

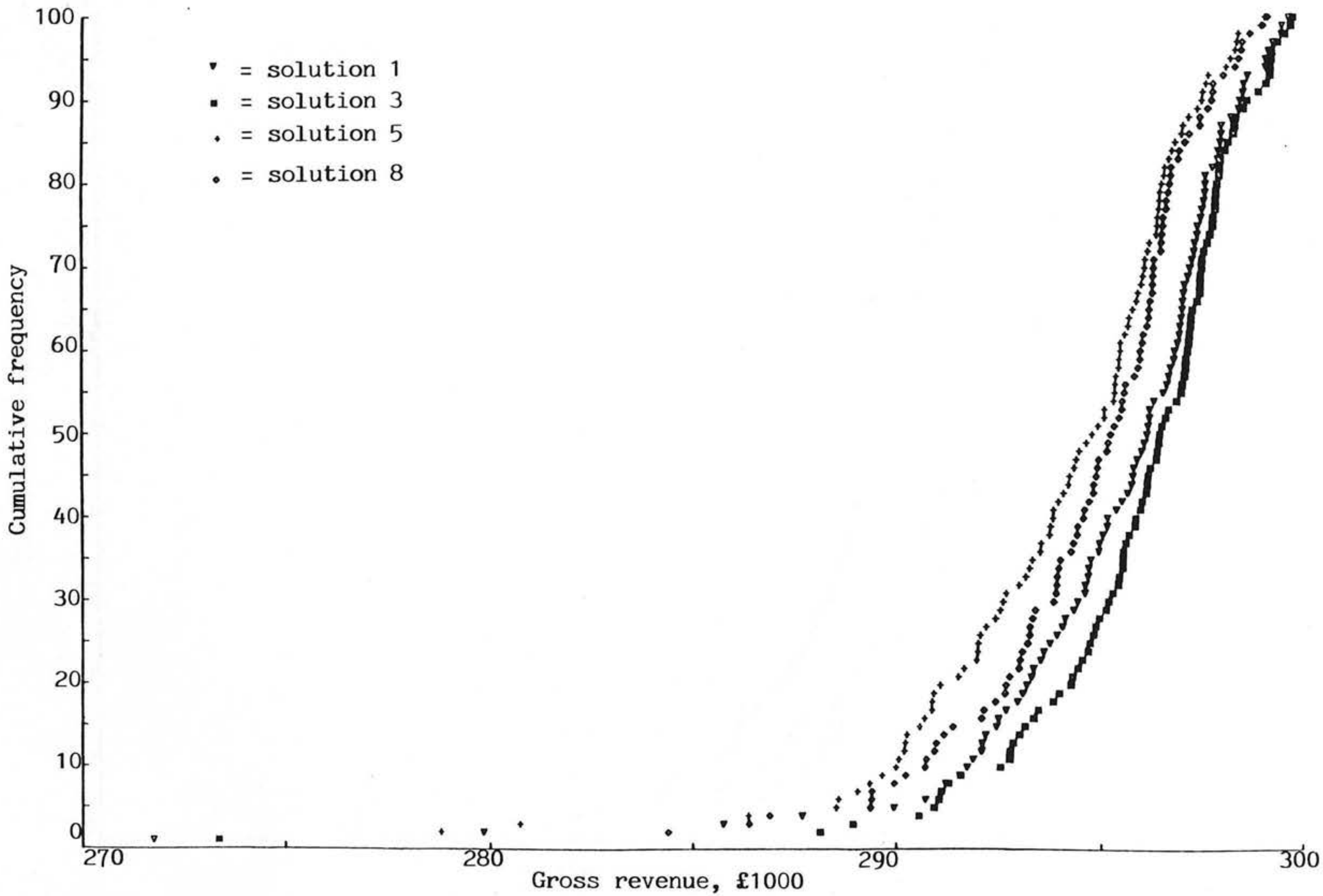

Fig 4.13 First order stochastic dominance of selected sets

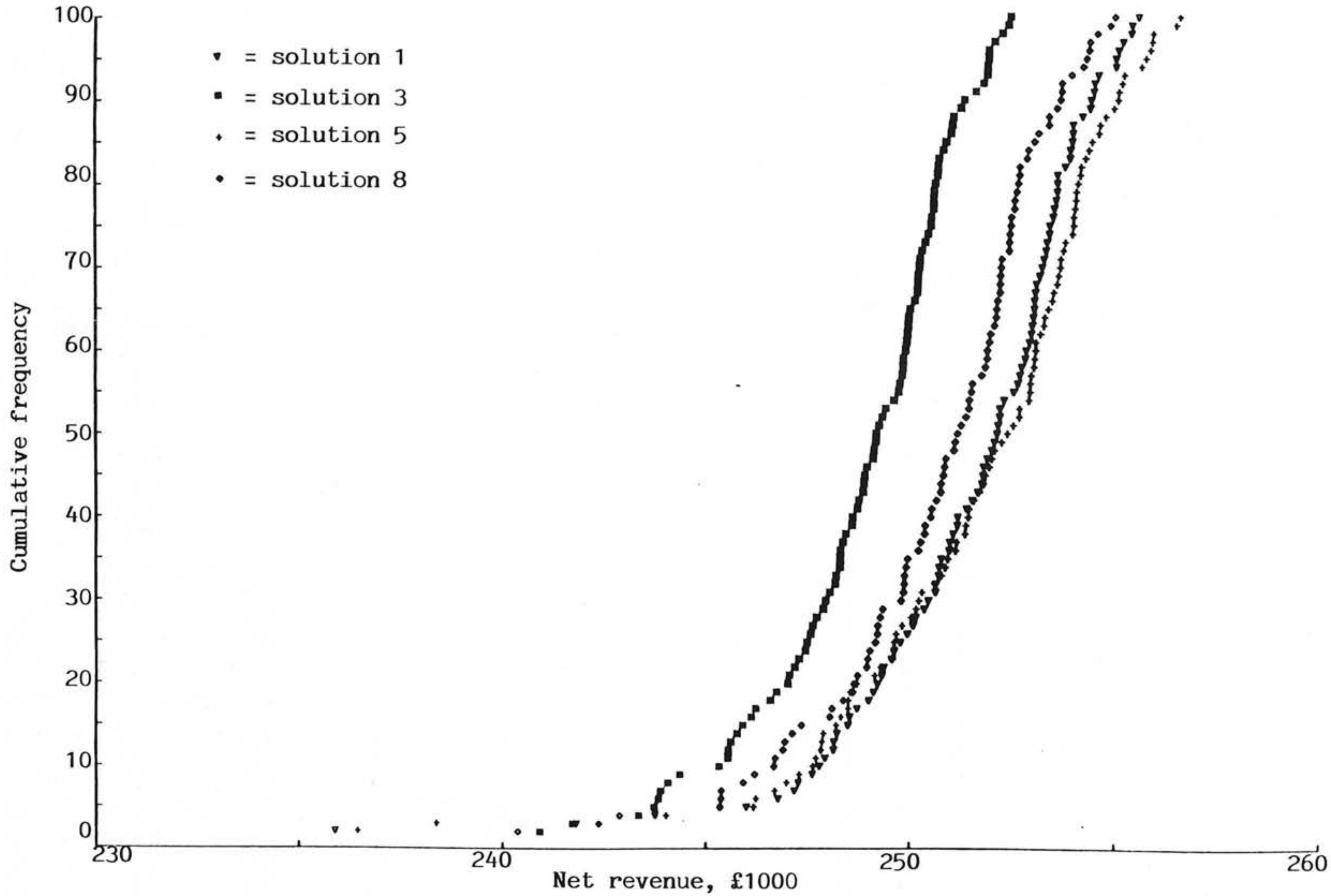

Fig 4.14 Second order stochastic dominance of selected sets

averse farmers. Figure 4.14 shows the stochastic dominance of the four solutions selected in Figure 4.13 reduced by their annual and fuel costs. Solution 1 heads the list with the highest maximum profit. The largest machinery sets (solution 3), first on the gross revenue ranking, is last on the net revenue with the lower maximum profit. Table 4.23 shows the ranking of the second order stochastic dominance. The annual costs of operations using farm machinery are derived from the costing routine procedure used in section 4.1 which is based on the annual hours used for each operation. The hours of use are determined by the size of the job. The annual cost of an item of equipment or machine cannot be determined without knowing the exact number of hours used during the different operations performed within a year.

5. CONCLUSIONS

Variation in the rates of depreciation, repairs and taxation has a significant effect on the annual costs of owning and operating farm machinery. A high initial rate of depreciation leads to unrealistically high annual costs during the early period of ownership and defers replacement. A new analytical procedure, called decremental depreciation, accurately predicts the loss in value with age of self propelled machinery. The inclusion of the appropriate resale values not only advances the optimum time for machine replacement but also makes variation in annual costs over the period of ownership much less sensitive to age of machine.

High repair costs through over-estimation or heavy usage encourage earlier machine replacement. High tax liability decreases the annual ownership costs and encourages earlier machine replacement, even though the minimum costs relate to similar periods of ownership.

The assessment of ploughing costs involves the calculation of tractor traction, plough draught and operating costs. In order to avoid discontinuities in the ploughing cost contours, the economic analysis is restricted to two-wheel drive tractors with fully mounted ploughs. Four sizes of tractors (45 kW, 61 kW, 74 kW and 94 kW) have been selected. Weight transfer reduces the tractive efficiency for tractors above 74 PTO kW and incurs a financial penalty. For any given rate of work, a higher speed with a narrower plough is most cost effective.

Integer linear programming is employed as a powerful technique for selecting sets of machinery for a particular farm size using minimum cost as the objective function. In order to maximise profit, the effect of random and stochastic variables, namely weather and crop yield, is considered by means of simulation.

Level of risk is determined by analysis of the various outcomes from the farm simulation. First and second order stochastic dominance are used to determine an indominant or efficient set of machinery.

In a simulation experiment on a 250 ha farm cropping cereals and potatoes from the alternative solutions obtained and ranked according to gross revenue, the highest income is obtained by the largest and most expensive set of machinery. The difference between the highest and lowest gross revenue curves is due to the variation in timeliness penalties for different sizes of machines. The annual costs of operating farm machinery are based on the annual hours of use which are determined depending on the size of tasks. After deducting the annual costs and the fuel costs of machinery operations, the second order stochastic dominance ranking is used to identify the maximum profit. The cumulative net revenue curves cross which demonstrate that the largest machinery sets which are highest on the gross revenue ranking, are the lowest on the net revenue for maximising profit. Again, the range of net revenue curves is relatively modest, at approximately 2%, because the machinery sets were selected on the basis of minimum cost so that extravagant and frugal systems are discarded early in the selection procedure.

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7. APPENDICES

APPENDIX A1

Farm machinery ownership cost model

```
c           MACHINERY SPECIFICATIONS
            ________________________

c
      OPEN(UNIT=LUDA,NAME='MCDMS.DAT',TYPE='UNKNOWN',DISPOSE='SAVE',
     &       ACCESS='DIRECT',CARRIAGE CONTROL='NONE',FORM='UNFORMATTED',
     &       RECORDSIZE=MSRL,ASSOCIATE VARIABLE=NDAR,MAXREC=MAXMS)
c
c     Read data from file.
c
      READ(LUDA'MSREC) TYPE
c
      WRITE(LUTT,10)
      WRITE(LUTT,20)
   10 FORMAT(1H0,'  MACHINE TYPE                ')
   20 FORMAT(1H ,'  --------------------------')
c
c     Machine type.
c     Units: none.
c
   30 CALL LINE(LUTT)
      WRITE(LUTT,50)
      WRITE(LUTT,60)
      WRITE(LUTT,70)
      WRITE(LUTT,80)
      WRITE(LUTT,90)
      WRITE(LUTT,100)
      WRITE(LUTT,110) TYPE
   50 FORMAT(1H ,'    Tractor            (TR)')
   60 FORMAT(1H ,'    Combine            (CB)')
   70 FORMAT(1H ,'    Moulb.plough       (PL)')
   80 FORMAT(1H ,'    Disk harrow        (DH)')
   90 FORMAT(1H ,'    Grain drill        (DR)')
  100 FORMAT(1H ,'    Rotary hoe         (RH)')
  110 FORMAT(1H ,'    Special implement (SL)',A,$)
      RARRAY(1) = TR
      RARRAY(2) = CB
      RARRAY(3) = PL
      RARRAY(4) = DH
      RARRAY(5) = DR
      RARRAY(6) = RH
      RARRAY(7) = SL
      CALL PGA(LUTT,LUTT,5,TYPE,4,11,RARRAY,7,ERROR)
      IF (ERROR.NE.0) GOTO 30
c
      WRITE(LUDA'MSREC) TYPE
c
      RETURN
c
      END
```

```
c          MACHINERY INPUT DATA
c          ____________________

      OPEN(UNIT=LUDA,NAME='CD.DAT',TYPE='OLD',DISPOSE='SAVE',
     &       ACCESS='DIRECT',CARRIAGE CONTROL='NONE',FORM='UNFORMATTED',
     &       RECORDSIZE=CDRL,ASSOCIATE VARIABLE=NDAR,MAXREC=MAXCD)
c
      WRITE(LUTT,10)
      WRITE(LUTT,20)
   10 FORMAT(1H0,'   Machine data             ')
   20 FORMAT(1H ,'   -----------------------')
c
c
c     Record number.
c     Units: none
c
c     Prevent record number 0 being selected.
      IF (CDREC.EQ.0) CDREC=1
   21 CALL LINE(LUTT)
      WRITE(LUTT,25)
   25 FORMAT(1H ,'  machine number          ',$)
      CALL PGI(LUTT,LUTT,5,CDREC,4,11,1,MAXCD,ERROR)
      IF (ERROR.NE.0) GOTO 21
c
c     Read data from file.
c
      READ(LUDA'CDREC) MPP,IL,IR,IV,TX,FCL,LCH,SH,PTO,AAP,AAS,USEH,
     &                 AS,AR,BS,BR,PUR,OS,FS,K1,K2
c
   30 WRITE(LUTT,40)
   40 FORMAT(1H ,'  machine price        ($)',$)
      CALL PGR(LUTT,LUTT,2,MPP,10.2,8,100.00,100000.00,ERROR)
      IF(ERROR.NE.0) GOTO 30
c
   50 WRITE(LUTT,60)
   60 FORMAT(1H ,'  loan interest rate       ',$)
      CALL PGR(LUTT,LUTT,2,IL,12.4,6,0.0000,1.0000,ERROR)
      IF(ERROR.NE.0) GOTO 50
c
   70 WRITE(LUTT,80)
   80 FORMAT(1H ,'  inflation rate           ',$)
      CALL PGR(LUTT,LUTT,2,IR,12.4,6,0.0000,1.0000,ERROR)
      IF(ERROR.NE.0) GOTO 70
c
   90 WRITE(LUTT,100)
  100 FORMAT(1H ,'  investment rate          ',$)
      CALL PGR(LUTT,LUTT,2,IV,12.4,6,0.0000,1.0000,ERROR)
      IF(ERROR.NE.0) GOTO 90
c
  110 WRITE(LUTT,120)
  120 FORMAT(1H ,'  tax rate                 ',$)
      CALL PGR(LUTT,LUTT,2,TX,10.2,8,0.00,100.00,ERROR)
      IF(ERROR.NE.0) GOTO 110
c
  130 WRITE(LUTT,140)
  140 FORMAT(1H ,'  fuel cost            ($/l)',$)
      CALL PGR(LUTT,LUTT,2,FCL,10.2,8,0.00,0.60,ERROR)
      IF(ERROR.NE.0) GOTO 130
c
  150 WRITE(LUTT,160)
  160 FORMAT(1H ,'  labour cost          ($/h)',$)
      CALL PGR(LUTT,LUTT,2,LCH,10.2,8,0.00,10.00,ERROR)
      IF(ERROR.NE.0) GOTO 150
```

```
c
  170 WRITE(LUTT,180)
  180 FORMAT(1H ,'  shelter cost         (%)',$)
      CALL PGR(LUTT,LUTT,2,SH,10.2,8,0.0,0.5,ERROR)
      IF(ERROR.NE.0) GOTO 170
c
  190 WRITE(LUTT,200)
  200 FORMAT(1H ,'  power                (kw)',$)
      CALL PGI(LUTT,LUTT,5,PTO,4,11,10,250,ERROR)
      IF(ERROR.NE.0) GOTO 190
c
  210 WRITE(LUTT,220)
  220 FORMAT(1H ,'  purchase age       (year)',$)
      CALL PGI(LUTT,LUTT,5,AAP,4,11,0,15,ERROR)
      IF(ERROR.NE.0) GOTO 210

  230 WRITE(LUTT,240)
  240 FORMAT(1H ,'  resale age         (year)',$)
      CALL PGI(LUTT,LUTT,5,AAS,4,11,AAP,15,ERROR)
      IF (ERROR.NE.0) GOTO 230
c
  290 WRITE(LUTT,300)
  300 FORMAT(1H ,'  used hours            (h)',$)
      CALL PGR(LUTT,LUTT,2,USEH,10.2,8,0.00,15000.00,ERROR)
      IF(ERROR.NE.0) GOTO 290
c
  310 WRITE(LUTT,320)
  320 FORMAT(1H ,'  resale coefficient  "As"',$)
      CALL PGR(LUTT,LUTT,2,AS,11.3,7,0.000,500.000,ERROR)
      IF(ERROR.NE.0) GOTO 310
c
  330 WRITE(LUTT,340)
  340 FORMAT(1H ,'  resale coefficient  "Bs"',$)
      CALL PGR(LUTT,LUTT,2,BS,11.3,7,0.000,500.000,ERROR)
      IF(ERROR.NE.0) GOTO 330
c
  342 WRITE(LUTT,345)
  345 FORMAT(1H ,'  resale coefficient  "k1"',$)
      CALL PGR(LUTT,LUTT,2,K1,11.3,7,0.000,1.000,ERROR)
      IF(ERROR.NE.0) GOTO 342
  347 WRITE(LUTT,348)
  348 FORMAT(1H ,'  resale coefficient  "k2"',$)
      CALL PGR(LUTT,LUTT,2,K2,12.4,6,0.0000,1.0000,ERROR)
      IF(ERROR.NE.0) GOTO 347
c
  350 WRITE(LUTT,360)
  360 FORMAT(1H ,'  repair coefficient  "Ar"',$)
      CALL PGR(LUTT,LUTT,2,AR,11.3,7,0.000,500.000,ERROR)
      IF(ERROR.NE.0) GOTO 350
c
  370 WRITE(LUTT,380)
  380 FORMAT(1H ,'  repair coefficient  "Br"',$)
      CALL PGR(LUTT,LUTT,2,BR,11.3,7,0.000,500.000,ERROR)
      IF(ERROR.NE.0) GOTO 370

  390 WRITE(LUTT,400)
  400 FORMAT(1H ,'  power utilisation    (%)',$)
      CALL PGR(LUTT,LUTT,2,PUR,10.2,8,0.00,1.00,ERROR)
      IF(ERROR.NE.0) GOTO 390

c
  410 WRITE(LUTT,420)
  420 FORMAT(1H ,'  operation speed   (km/h)',$)
      CALL PGR(LUTT,LUTT,2,OS,10.2,8,0.00,20.00,ERROR)
```

```
      IF(ERROR.NE.0) GOTO 410
c
  430 WRITE(LUTT,440)
  440 FORMAT(1H ,'  field speed        (km/h)',$)
      CALL PGR(LUTT,LUTT,2,FS,10.2,8,0.00,20.00,ERROR)
      IF(ERROR.NE.0) GOTO 430
c
      WRITE(LUDA'CDREC)  MPP,IL,IR,IV,TX,FCL,LCH,SH,PTO,AAP,AAS,USEH,
     &                   AS,AR,BS,BR,PUR,OS,FS,K1,K2
c
c
      RETURN
c
      END
```

```
c
C          TECHNICAL CALCULATION
c          _____________________
c     Open data files.
c
      OPEN(UNIT=LUDA,NAME='CD.DAT',TYPE='OLD',DISPOSE='SAVE',
     &      ACCESS='DIRECT',CARRIAGE CONTROL='NONE',FORM='UNFORMATTED',
     &      RECORDSIZE=CDRL,ASSOCIATE VARIABLE=NDAR,MAXREC=MAXCD)
c     Read machine cost data from files, MCD.
c
      CDREC = 1
c
      READ(LUDA'CDREC) MPP,IL,IR,IV,TX,FCL,LCH,SH,PTO,AAP,AAS,USEH,
     &                 AS,AR,BS,BR,PUR,OS,FS,K1,K2
c
      CLOSE(UNIT=LUDA)
c
      OPEN(UNIT=LUDA,NAME='MCDMS.DAT',TYPE='OLD',DISPOSE='SAVE',
     &      ACCESS='DIRECT',CARRIAGE CONTROL='NONE',FORM='UNFORMATTED',
     &      RECORDSIZE=MSRL,ASSOCIATE VARIABLE=NDAR,MAXREC=MAXMS)
c
      READ(LUDA'MSREC) TYPE
c
      CLOSE(UNIT=LUDA)
c
      OPEN(UNIT=LUDA,NAME='MCDD.DAT',TYPE='NEW',DISPOSE='SAVE',
     &     ACCESS='DIRECT',CARRIAGE CONTROL='NONE',FORM='UNFORMATTED',
     &     RECORDSIZE=DDRL,ASSOCIATE VARIABLE=NDAR,MAXREC=MAXDD)
      N=AAS
      USE=1000.0
c
      IF(TYPE.EQ.TR) GOTO 100
      IF(TYPE.EQ.CB) GOTO 105
      IF(TYPE.EQ.PL) GOTO 120
      IF(TYPE.EQ.DH) GOTO 130
      IF(TYPE.EQ.DR) GOTO 140
      IF(TYPE.EQ.RH) GOTO 150
      IF(TYPE.EQ.SL) GOTO 1234
c
c     Tractor repair and resale coefficients.
c     Units:none.
c
  100 AR = 0.012
      BR = 2.0
C?      AS = 78.2
C?      BS = 0.825
c
      GOTO 1234
c
c     Combine self-propelled repair and resale coefficients.
c     Units:none.
c
  105 AR = 0.12
      BR = 2.1
C?      AS = 64.0
C?      BS = 0.885
c
      GOTO 1234
c
c     Moulboard plough repair and resale coefficients.
c     Units:none.
c
  120 AR = 0.430
```

```
      BR = 1.8
      AS = 60.0
      BS = 0.885
c
      GOTO 1234
c
c     Disk harrow repair and resale coefficients.
c     Units:none.
c
  130 AR = 0.18
      BR = 1.7
      AS = 60.0
      BS = 0.885
c
      GOTO 1234
c
c     Grain drill repair and resale coefficients.
c     Units:none.
c
  140 AR = 0.54
      BR = 2.1
      AS = 60.0
      BS = 0.885
c
      GOTO 1234
c
c     Rotary hoe repair and resale coefficients.
c     Units:none.
c
  150 AR = 0.23
      BR = 1.4
      AS = 60.0
      BS = 0.885
c
      GOTO 1234
c
 1234 CONTINUE
c
c     Close data file.
c
      CLOSE(UNIT=LUDA)
c
c     Calculate machine resale value.
c     Units:currency units.
c
C?      IF (TYPE.EQ.TR) SV=MPP*(EXP(-K*N))
      IF (TYPE.EQ.TR) SV=MPP*((EXP(-K1*N))*(EXP(K2*(N**2))))
C?      IF (TYPE.EQ.CB) SV=MPP*(EXP(-K*N))
      IF (TYPE.EQ.CB) SV=MPP*(EXP((-K1*N)+(K2*(N**2))))
      IF (TYPE.EQ.PL) SV=AS*(BS**N)*MPP/100.0
      IF (TYPE.EQ.DH) SV=AS*(BS**N)*MPP/100.0
      IF (TYPE.EQ.DR) SV=AS*(BS**N)*MPP/100.0
      IF (TYPE.EQ.RH) SV=AS*(BS**N)*MPP/100.0
      IF (TYPE.EQ.SL) SV=AS*(BS**N)*MPP/100.0
c

      WW = 0.0
      TCA=0.0
      TCAD=0.0
      REPP=0.0
      TIC =  0
      TREPC=0
      TINS=0
      SUM=0
```

```
      DO 900 I = 1,N
c
      INFR = ((1+IR)**I)
      INVR = ((1+IV)**I)
      W =INFR/INVR
      WW=WW+W
c
c     Calculate % of repair cost.
c     Units:none.
      AREPP=((AR/(FS**BR))*((((I*USEH/1000.0)*OS)**BR)-((((I-1)*
     &       USEH/1000.0)*OS)**BR))*100.0)

      REPC=AREPP*(MPP/100.0)
      REPP= REPP + AREPP
      TREPC= TREPC + (REPC*((1+IR)**I)/((1+IV)**I))
c
c     Calculate annual capital allowance.
c     Units:currency units.
c
      ACA=0.25*(0.75**(I-1))*MPP
      TCA=TCA + ((0.25*(0.75**(I-1)))*MPP)
      TCAD = TCAD + (ACA/((1+IV)**I))
c
c     Calculate annual interest charge.
c     Units:currency units.
c
      AIC = MPP*(((1+IL)**N)-((1+IL)**(I-1)))*IL/(((1+IL)**N)-1)
      TIC = TIC + (AIC/((1+IV)**I))
c
c     Calculate present salvage value.
c     Units:currency units.
      IF (TYPE.EQ.TR) GO TO 155
      IF (TYPE.EQ.CB) GO TO 155
c
      PSV=AS*(BS**(I-1))*MPP/100.0
  155 PSV=MPP*((EXP(-K1*(I-1)))*(EXP(K2*((I-1)**2))))
      IF (PSV.LE.1000.0)  INS=25.0
      IF (PSV.GT.1000.0.AND.PSV.LE.5000.0) INS=25.0+(1.2*((PSV-1000.0)/
     &               100.0))
      IF (PSV.GT.5000.0.AND.PSV.LE.15000.0) INS=25.0+(1.2*40.0)+(0.95*((
     &    PSV-5000.0)/100.0))
      IF (PSV.GT.15000.0.AND.PSV.LE.40000.0) INS=25.0+(1.2*40.0)+(0.95*
     &    100.0)+(0.85*((PSV-15000.0)/100.0))

c     Calculate total insurance.
c     Units:currency units.
c
      TINS = TINS + (INS*((1+IR)**I)/((1+IV)**I))
c
c     Calculate repair and insurance cost.
c     Units:currency units.
c
      RAINC=REPC+INS
c
c     Calculate actual repair and insurance cost.
c     Units:currency units.
c
      ARAINC=RAINC*INFR

c     Calculate actual resale value.
c     Units:currency units.
c
      IF (I.LT.N) GOTO 2
      ASV=SV*((1+IR)**N)
```

```
      DASV = ASV/((1+IV)**N)

c     Calculate balancing charge.
c     Units: currency units.

      BC = TCA+ASV-MPP
      DBC = BC/((1+IV)**N)

c     Calculate mortgage repayment value.
c     Units:currency units.

    2 MORV=(MPP*((1+IL)**N)*IL)/(((1+IL)**N)-1)


c     Calculate total tax allowances.
c     Units:currency units.
c
      TTA=ARAINC+ACA+AIC-BC

c     Calculate total tax relief.
c     Units:currency units.
c
      TTR=TTA*TX

c     Calculate actual cash outgoing.
c     Units:currency units.
c
      ACOUT=MORV+ARAINC-ASV-TTR

c     Calculate discount cash flow.
c     Units:currency units.
c
      DCFL=ACOUT/INVR

c     Calculate total discount cash flow.
c     Units:currency units.

      SUM=SUM+DCFL

c     Calculate net present mortgage value.
c     Units: currency units.
c
      NPMV = MPP*(IL/IV)*(((1+IL)**N)/((1+IV)**N))*((((1+IV)**N)-1)/(((
     &       1+IL)**N)-1))
c
c     Calculate present annual cost.
c     Units: currency units.
c
       IF(I.LT.N) GOTO 4
       PANC=SUM/WW
    4  PKW=PUR*PTO
c
c     Calculate fuel cost.
c     Units:currency units.
      IF (TYPE.NE.TR.OR.TYPE.NE.CB) GOTO 12
c
      FC=(2.64*PUR+3.91-0.2*((738*PUR+173)**0.5))*PKW*USEH*FCL

c     Calculate labour cost.
c     Units:currency units.
c
      LC=USEH*LCH

c     Calculate shelter cost.
```

```
c     Units:currency units.
c
  12  SHC = SH*MPP
c
c     Calculate total cost.
c     Units:currency units.
c
      TC=PANC+FC+LC+SHC
c

c     Calculate present annual cost from general equation.
c     Units: currency units.
c
      IF (I.LT.N) GOTO 3
      PANNC = (NPMV-(TX*(TCAD+TIC))+(DBC*TX)+((1-TX)*(TREPC+TINS))-
     &        DASV)/WW

    3 CONTINUE

      WRITE(5,200)  I,MPP,IL,INFR,INVR,REPC,INS,RAINC,SV,MORV,ARAINC,
     &              ASV,ACA,TCA,BC,AIC,TTA,TTR,ACOUT,DCFL,PANC,
     &              W,FC,LC,SHC,TC,
     &              NPMV,REPP,TREPC,TINS,TCAD,DBC,DASV,PANNC
  200 FORMAT(1H0 ,  I4,F8.1,3(F6.2),F9.2,5(F8.2),3(F9.2),12(F10.2),
     &              F10.2,F7.2,6(F10.2))
c
      WRITE(6,455) I,INFR,INVR,REPC,INS,ARAINC,ACA,AIC,TTA,TTR,ACOUT,
     &             DCFL,W
  455 FORMAT(1H , I2,F7.3,F8.3,F8.2,F7.2,F8.2,2(F9.2),4(F8.2),F8.3)

c
  900 CONTINUE

      WRITE(LURT,199) TYPE
      WRITE(LURT,195)
      WRITE(LURT,111)  MPP,USEH
      WRITE(LURT,112)  IL,IV,IR
      WRITE(LURT,113)  TX
      WRITE(LURT,114)  FCL,LCH,SH
      WRITE(LURT,115)  AR,BR
      WRITE(LURT,116)  AS,BS
      WRITE(LURT,118) K1,K2
      WRITE(LURT,117) TYPE
  199 FORMAT(1H0,' Input data of: ',  4(A4),' - ')
  195 FORMAT(1H , 19('_'))
  111 FORMAT(1H0,' Purchase price ($) = ',F9.2,'
     &                            Used hours   (h/yr) = ',F9.2)
  112 FORMAT(1H0 ,' Loan rate        = ',F6.4,'    Interest rate      =
     & ',F6.4,'    Inflation rate     = ',F6.4)
  113 FORMAT(1H ,' Tax rate         = ',F6.2)
  114 FORMAT(1H0,' Fuel cost  ($/l)= ',F6.2,'      Labour cost  ($/h)=
     & ',F6.2,'    Shelter          (%) = ',F6.2)
  115 FORMAT(1H0,' Repair coefficients:   Ar  = ',F6.3,'
     & Br  = ',F6.3)
  116 FORMAT(1H ,' Resale coefficients:   As  = ',F6.3,'
     &                Bs  = ',F6.3)
  118 FORMAT(1H ,' Resale coefficients:   k1  = ',F6.3,'
     &                k2  = ',F6.3)

  117 FORMAT(1H0,' Output cost data : ', 4(A4),'  ')
      CLOSE(UNIT=5)
      CLOSE(UNIT=6)
c
      OPEN(UNIT=6,NAME='MCCALC6.RES',TYPE='UNKNOWN',
```

```
     &      ACCESS='SEQUENTIAL',FORM='FORMATTED',RECL=512)
c
      WRITE(LURT,131)
  131 FORMAT(1H0,101('-'))
c
      WRITE(LURT,132)
      WRITE(LURT,133)
      WRITE(LURT,134)
      WRITE(LURT,135)
      WRITE(LURT,136)
      WRITE(LURT,137)
  132 FORMAT(1H ,'Age Infla- Invest- Repair Insur- Actual    Actual   Ac
     &tual   Total  Total   Actual Discount Inflated')
  133 FORMAT(1H ,'      tion    ment    cost    ance  repair & capital in
     &terest   tax   tax    cash     cash  discount')
  134 FORMAT(1H ,'     factor  factor',15x,'insuran-  allow-   charge al
     &low- relief outgoing   flow    factor')
  135 FORMAT(1H ,36x,'ce        ance',13x,'ance')
  136 FORMAT(1H ,'Yr',20x,'$       $       $        $        $        $
     &    $        $        $        %')
  137 FORMAT(1H ,101('-'))
c
      DO 103 II = 1,N
      READ(6,555) I,INFR,INVR,REPC,INS,ARAINC,ACA,AIC,TTA,TTR,ACOUT,
     &            DCFL,W
  555 FORMAT(1H ,I2,F7.3,F8.3,F8.2,F7.2,F8.2,2(F9.2),4(F8.2),F8.3)
      WRITE(LURT,666) II,INFR,INVR,REPC,INS,ARAINC,ACA,AIC,TTA,TTR,
     &                ACOUT,DCFL,W
  666 FORMAT(1H ,I2,F7.3,F8.3,F8.2,F7.2,F8.2,2(F9.2),4(F8.2),F8.3)
c
  103 CONTINUE
c
      WRITE(LURT,110)
  110 FORMAT(1H ,  101('_'))
      WRITE(LURT,210) ASV,SUM,WW
      WRITE(LURT,211) MORV
      WRITE(LURT,212) BC
      WRITE(LURT,213) PANC
      WRITE(LURT,214) FC
      WRITE(LURT,215) LC
      WRITE(LURT,216) SHC
      WRITE(LURT,217)
      WRITE(LURT,218) TC
  210 FORMAT(1H0 ,' Actual salvage value   ($) = ',F8.2,44x,F10.2,' /',
     &F6.3)
  211 FORMAT(1H ,' Mortgage payment       ($) = ',F8.2)
  212 FORMAT(1H ,' Actual balancing chrge ($) = ',F8.2)
  213 FORMAT(1H0,60x,'Present annual cost ($) = ',F9.2)
  214 FORMAT(1H0,60x,'Fuel cost           ($) = ',F9.2)
  215 FORMAT(1H0,60x,'Labour cost         ($) = ',F9.2)
  216 FORMAT(1H0,60x,'Shelter cost        ($) = ',F9.2)
  217 FORMAT(1H ,87x,9('-'))
  218 FORMAT(1H0,60x,'Total cost          ($) = ',F9.2)

      RETURN
      END
```

APPENDIX A2

Annual ownership costs calculation for a 60 kW two-wheel drive tractor with an initial price of £16000.
Ownership period from 1 to 10 years without taxation

Input data of: TR

Purchase price ($) = 16000.00 Used hours (h/yr) = 1000.00

Loan rate = 0.1130 Interest rate = 0.0815 Inflation rate = 0.0500
Tax rate = 0.00

Fuel cost ($/L)= 0.13 Labour cost ($/h)= 5.00 Shelter = 0.01

Repair coefficients: Ar = 0.012 Br = 2.000
Resale coefficients: As = 68.000 Bs = 0.920
Resale coefficients: k1 = 0.237 k2 = 0.005

Output cost data : TR

Age	Infla-tion factor	Invest-ment factor	Repair cost	Insur-ance	Actual repair & insurance	Actual capital allow-ance	Actual interest charge	Total tax allow-ance	Total tax relief	Actual cash outgoing	Discount cash flow	Inflated discount factor
Yr			$	$	$	$	$	$	$	$	$	%
1	1.050	1.082	192.00	176.50	386.93	4000.00	1808.00	4873.43	0.00	4873.43	4506.17	0.971

4506.17 / 0.971

Actual salvage value ($) = 13321.49
Mortgage payment ($) = 17807.99
Actual balancing chrge ($) = 1321.49

Present annual cost ($) = 4641.36

Fuel cost ($) = 2359.21

Labour cost ($) = 5000.00

Shelter cost ($) = 160.00

Input data of: TR

Purchase price ($) = 16000.00 Used hours (h/yr) = 1000.00

Loan rate = 0.1130 Interest rate = 0.0815 Inflation rate = 0.0500
Tax rate = 0.00

Fuel cost ($/L)= 0.13 Labour cost ($/h)= 5.00 Shelter = 0.01

Repair coefficients: Ar = 0.012 Br = 2.000
Resale coefficients: As = 68.000 Bs = 0.920
Resale coefficients: k1 = 0.237 k2 = 0.005

Output cost data : TR

Age Yr	Inflation factor	Investment factor	Repair cost $	Insurance $	Actual repair & insurance $	Actual capital allowance $	Actual interest charge $	Total tax allowance $	Total tax relief $	Actual cash outgoing $	Discount cash flow $	Inflated discount factor %
1	1.050	1.082	192.00	176.50	386.93	4000.00	1808.00	6194.92	0.00	9767.09	9031.06	0.971
2	1.102	1.170	576.00	146.03	796.04	3000.00	952.34	2545.52	0.00	-1026.65	-877.75	0.943

Actual salvage value ($) = 11202.86
Mortgage payment ($) = 9380.17
Actual balancing chrge ($) = 2202.86

8153.31 / 1.913

Present annual cost ($) = 4261.01

Fuel cost ($) = 2359.21

Labour cost ($) = 5000.00

Shelter cost ($) = 160.00

Input data of: TR

Purchase price ($) = 16000.00 Used hours (h/yr) = 1000.00

Loan rate = 0.1130 Interest rate = 0.0815 Inflation rate = 0.0500
Tax rate = 0.00

Fuel cost ($/l) = 0.13 Labour cost ($/h) = 5.00 Shelter = 0.01

Repair coefficients: Ar = 0.012 Br = 2.000
Resale coefficients: As = 68.000 Bs = 0.920
Resale coefficients: k1 = 0.237 k2 = 0.005

Output cost data : TR

Age Yr	Infla-tion factor	Invest-ment factor	Repair cost $	Insur-ance $	Actual repair & insurance $	Actual capital allowance $	Actual interest charge $	Total tax allowance $	Total tax relief $	Actual cash outgoing $	Discount cash flow $	Inflated discount factor %
1	1.050	1.082	192.00	176.50	386.93	4000.00	1808.00	5194.92	0.00	6968.52	6443.39	0.971
2	1.102	1.170	576.00	146.03	796.04	3000.00	1268.58	5064.62	0.00	7377.63	6307.60	0.943
3	1.158	1.265	960.00	122.03	1252.59	2250.00	668.21	1404.95	0.00	-1681.67	-1329.41	0.915

Actual salvage value ($) = 9515.85
Mortgage payment ($) = 6581.60
Actual balancing chrge ($) = 2765.85

11421.57 / 2.829

Present annual cost ($) = 4037.87

Fuel cost ($) = 2359.21

Labour cost ($) = 5000.00

Shelter cost ($) = 160.00

Input data of: TR

Purchase price ($) = 16000.00 Used hours (h/yr) = 1000.00

Loan rate	= 0.1130	Interest rate	= 0.0815	Inflation rate	= 0.0500
Tax rate	= 0.00				
Fuel cost ($/L)=	0.13	Labour cost ($/h)=	5.00	Shelter	= 0.01

Repair coefficients:	Ar = 0.012	Br = 2.000
Resale coefficients:	As = 68.000	Bs = 0.920
Resale coefficients:	k1 = 0.237	k2 = 0.005

Output cost data : TR

Age Yr	Infla-tion factor	Invest-ment factor	Repair cost $	Insur-ance $	Actual repair & insurance $	Actual capital allow-ance $	Actual interest charge $	Total tax allow-ance $	Total tax relief $	Actual cash outgoing $	Discount cash flow $	Inflated discount factor %
1	1.050	1.082	192.00	176.50	386.93	4000.00	1808.00	6194.92	0.00	5577.22	5156.93	0.971
2	1.102	1.170	576.00	146.03	796.04	3000.00	1425.80	5221.84	0.00	5986.33	5118.08	0.943
3	1.158	1.265	960.00	122.03	1252.59	2250.00	1000.41	4503.00	0.00	6442.88	5093.31	0.915
4	1.216	1.368	1344.00	103.59	1759.56	1687.50	526.96	872.39	0.00	-1214.27	-887.59	0.888

Actual salvage value ($) = 8164.12
Mortgage payment ($) = 5190.29
Actual balancing chrge ($) = 3101.62

14480.74 / 3.717

Present annual cost ($) = 3895.71

Fuel cost ($) = 2359.21

Labour cost ($) = 5000.00

Shelter cost ($) = 160.00

Input data of: TR

Purchase price ($) = 16000.00   Used hours (h/yr) = 1000.00

Loan rate	= 0.1130	Interest rate	= 0.0815	Inflation rate	= 0.0500
Tax rate	= 0.00				
Fuel cost ($/L) =	0.13	Labour cost ($/h) =	5.00	Shelter	= 0.01

Repair coefficients:	Ar = 0.012		Br = 2.000	
Resale coefficients:	As = 68.000		Bs = 0.920	
Resale coefficients:	k1 = 0.237		k2 = 0.005	

Output cost data : TR

Age	Infla-tion factor	Invest-ment factor	Repair cost	Insur-ance	Actual repair & insuran-ce	Actual capital allow-ance	Actual interest charge	Total tax allow-ance	Total tax relief	Actual cash outgoing	Discount cash flow	Inflated discount factor
Yr			$	$	$	$	$	$	$	$	$	λ
1	1.050	1.082	192.00	176.50	386.93	4000.00	1808.00	6194.92	0.00	4748.77	4390.91	0.971
2	1.102	1.170	576.00	146.03	796.04	3000.00	1519.42	5315.45	0.00	5157.88	4409.79	0.943
3	1.158	1.265	960.00	122.03	1252.59	2250.00	1198.22	4700.81	0.00	5614.43	4438.40	0.915
4	1.216	1.368	1344.00	103.59	1759.56	1687.50	840.73	4287.79	0.00	6121.40	4474.50	0.888
5	1.276	1.480	1728.00	89.31	2319.40	1265.63	442.85	749.94	0.00	-393.56	-266.00	0.863
											17447.60 /	4.580

Actual salvage value ($) = 7074.80
Mortgage payment ($) = 4361.84
Actual balancing chrge ($) = 3277.93

Present annual cost ($) = 3809.76

Fuel cost ($) = 2359.21

Labour cost ($) = 5000.00

Shelter cost ($) = 160.00

Input data of: TR

Purchase price ($) = 16000.00   Used hours (h/yr) = 1000.00

Loan rate = 0.1130   Interest rate = 0.0815   Inflation rate = 0.0500
Tax rate = 0.00

Fuel cost ($/L)= 0.13   Labour cost ($/h)= 5.00   Shelter = 0.01

Repair coefficients: Ar = 0.012   Br = 2.000
Resale coefficients: As = 68.300   Bs = 0.920
Resale coefficients: k1 = 0.237   k2 = 0.005

Output cost data : TR

Age Yr	Infla-tion factor	Invest-ment factor	Repair cost $	Insur-ance $	Actual repair & insuran-ce $	Actual capital allow-ance $	Actual interest charge $	Total tax allow-ance $	Total tax relief $	Actual cash outgoing $	Discount cash flow $	Inflated discount factor %
1	1.050	1.082	192.00	176.50	386.93	4000.00	1808.00	5194.92	0.00	4201.69	3885.06	0.971
2	1.102	1.170	576.00	146.03	796.04	3000.00	1581.24	5377.27	0.00	4610.80	3942.06	0.943
3	1.158	1.265	960.00	122.03	1252.59	2250.00	1328.85	4831.43	0.00	5067.35	4005.91	0.915
4	1.216	1.368	1344.00	103.59	1759.56	1687.50	1047.94	4494.99	0.00	5574.32	4074.61	0.888
5	1.276	1.480	1728.00	89.31	2319.40	1265.63	735.28	4320.31	0.00	6134.16	4145.94	0.863
6	1.340	1.600	2112.00	78.16	2935.02	949.22	387.30	926.76	0.00	557.35	348.31	0.837

Actual salvage value ($) = 6192.44
Mortgage payment ($) = 3814.77
Actual balancing chrge ($) = 3344.79

20401.90 / 5.417

Present annual cost ($) = 3766.14

Fuel cost ($) = 2359.21

Labour cost ($) = 5000.00

Shelter cost ($) = 160.00

Input data of: TR

Purchase price ($) = 16000.00 Used hours (h/yr) = 1000.00

Loan rate	= 0.1130	Interest rate	= 0.0815	Inflation rate	= 0.050
Tax rate	= 0.00				
Fuel cost ($/L)=	0.13	Labour cost ($/h)=	5.00	Shelter	= 0.01

Repair coefficients:	Ar	= 0.012	Br	= 2.000
Resale coefficients:	As	= 68.000	Bs	= 0.920
Resale coefficients:	k1	= 0.237	k2	= 0.005

Output cost data : TR

Age	Inflation factor	Investment factor	Repair cost	Insurance	Actual repair & insurance	Actual capital allowance	Actual interest charge	Total tax allowance	Total tax relief	Actual cash outgoing	Discount cash flow	Inflated discount factor
Yr			$	$	$	$	$	$	$	$	$	%
1	1.050	1.082	192.00	176.50	386.93	4000.00	1808.00	5194.92	0.00	3815.35	3527.83	0.971
2	1.102	1.170	576.00	146.03	796.04	3000.00	1624.89	5420.93	0.00	4224.46	3611.75	0.943
3	1.158	1.265	960.00	122.03	1252.59	2250.00	1421.09	4923.68	0.00	4681.01	3700.50	0.915
4	1.216	1.368	1344.00	103.59	1759.56	1687.50	1194.27	4641.32	0.00	5187.98	3792.21	0.888
5	1.276	1.480	1728.00	89.31	2319.40	1265.63	941.81	4526.83	0.00	5747.62	3884.81	0.863
6	1.340	1.600	2112.00	78.16	2935.02	949.22	660.82	4545.06	0.00	6363.45	3976.79	0.837
7	1.407	1.731	2496.00	68.45	3608.44	711.91	348.08	1329.57	0.00	1562.26	902.75	0.813

Actual salvage value ($) = 5474.60
Mortgage payment ($) = 3428.42
Actual balancing chrge ($) = 3338.86

23396.64 / 6.230

Present annual cost ($) = 3755.31

Fuel cost ($) = 2359.21

Labour cost ($) = 5000.00

Shelter cost ($) = 160.00

Input data of: TR

Purchase price ($) = 16000.00 Used hours (h/yr) = 1000.00

Loan rate = 0.1130 Interest rate = 0.0815 Inflation rate = 0.0500
Tax rate = 0.00

Fuel cost ($/L) = 0.13 Labour cost ($/h) = 5.00 Shelter = 0.01

Repair coefficients: Ar = 0.012 Br = 2.000
Resale coefficients: As = 68.000 Bs = 0.920
Resale coefficients: k1 = 0.237 k2 = 0.005

Output cost data : TR

Age Yr	Inflation factor	Investment factor	Repair cost $	Insurance $	Actual repair & insurance $	Actual capital allowance $	Actual interest charge $	Total tax allowance $	Total tax relief $	Actual cash outgoing $	Discount cash flow $	Inflated discount factor %
1	1.050	1.082	192.00	176.50	386.93	4000.00	1808.03	6194.92	0.00	3529.40	3263.43	0.971
2	1.102	1.170	576.00	146.03	796.04	3000.00	1657.20	5453.24	0.00	3938.51	3367.28	0.943
3	1.158	1.265	960.00	122.03	1252.59	2250.00	1489.37	4991.96	0.00	4395.06	3474.45	0.915
4	1.216	1.368	1344.00	103.59	1759.56	1687.50	1302.57	4749.62	0.00	4902.03	3583.19	0.888
5	1.276	1.480	1728.00	89.31	2319.40	1265.63	1094.66	4679.68	0.00	5461.87	3691.55	0.863
6	1.340	1.600	2112.00	78.16	2935.02	949.22	863.25	4747.50	0.00	6077.50	3798.09	0.837
7	1.407	1.731	2496.00	68.45	3608.44	711.91	605.70	4926.06	0.00	6750.91	3901.01	0.813
8	1.477	1.872	2880.00	59.69	4343.26	533.94	319.05	1909.43	0.00	2597.11	1387.65	0.789

Actual salvage value ($) = 4888.62
Mortgage payment ($) = 3142.48
Actual balancing chrge ($) = 3286.81

26466.64 / 7.020

Present annual cost ($) = 3770.34

Fuel cost ($) = 2359.21

Labour cost ($) = 5000.00

Shelter cost ($) = 160.00

Input data of: TR

Purchase price ($) = 16000.00 Used hours (h/yr) = 1000.00

Loan rate = 0.1130 Interest rate = 0.0815 Inflation rate = 0.0500
Tax rate = 0.00

Fuel cost ($/L)= 0.13 Labour cost ($/h)= 5.00 Shelter = 0.01

Repair coefficients: Ar = 0.012 Br = 2.000
Resale coefficients: As = 68.000 Bs = 0.920
Resale coefficients: k1 = 0.237 k2 = 0.005

Output cost data : TR

Age Yr	Infla-tion factor	Invest-ment factor	Repair cost $	Insur-ance $	Actual repair & insurance $	Actual capital allow-ance $	Actual interest charge $	Total tax allow-ance $	Total tax relief $	Actual cash outgoing $	Discount cash flow $	Inflated discount factor %
1	1.050	1.082	192.00	176.50	386.93	4000.00	1808.00	5194.92	0.00	3310.33	3060.87	0.971
2	1.102	1.170	576.00	146.03	796.04	3000.00	1681.96	5478.00	0.00	3719.44	3179.98	0.943
3	1.158	1.265	960.00	122.03	1252.59	2250.00	1541.68	5044.26	0.00	4175.99	3301.26	0.915
4	1.216	1.368	1344.00	103.59	1759.56	1687.50	1385.54	4832.60	0.00	4682.96	3423.06	0.888
5	1.276	1.480	1728.00	89.31	2319.40	1265.63	1211.76	4796.78	0.00	5242.80	3543.49	0.863
6	1.340	1.600	2112.00	78.16	2935.02	949.22	1018.35	4902.59	0.00	5858.43	3661.19	0.837
7	1.407	1.731	2496.00	68.45	3608.44	711.91	803.07	5123.43	0.00	6531.84	3774.42	0.813
8	1.477	1.872	2880.00	59.69	4343.26	533.94	563.48	5440.67	0.00	7266.06	3882.60	0.769
9	1.551	2.024	3264.00	52.71	5145.30	400.45	296.81	2634.68	0.00	3659.47	1807.92	0.766

29634.78 / 7.786

Actual salvage value ($) = 4409.23
Mortgage payment ($) = 2923.40
Actual balancing chrge ($) = 3207.87

Present annual cost ($) = 3806.11

Fuel cost ($) = 2359.21

Labour cost ($) = 5000.00

Shelter cost ($) = 160.00

Input data of: TR

Purchase price ($) = 16000.00 Used hours (h/yr) = 1000.00

Loan rate = 0.1130 Interest rate = 0.0815 Inflation rate = 0.0500
Tax rate = 0.00

Fuel cost ($/l)= 0.13 Labour cost ($/h)= 5.00 Shelter = 0.01

Repair coefficients: Ar = 0.012 Br = 2.000
Resale coefficients: As = 68.000 Bs = 0.920
Resale coefficients: k1 = 0.237 k2 = 0.005

Output cost data : TR

Age Yr	Inflation factor	Investment factor	Repair cost $	Insurance $	Actual repair & insurance $	Actual capital allowance $	Actual interest charge $	Total tax allowance $	Total tax relief $	Actual cash outgoing $	Discount cash flow $	Inflated discount factor %
1	1.050	1.082	192.00	176.50	386.93	4000.00	1808.00	6194.92	0.00	3138.01	2901.54	0.971
2	1.102	1.170	576.00	146.03	796.04	3000.00	1701.43	5497.47	0.00	3547.13	3032.66	0.943
3	1.158	1.265	960.00	122.03	1252.59	2250.00	1582.82	5085.41	0.00	4003.68	3165.04	0.915
4	1.216	1.368	1344.00	103.59	1759.56	1687.50	1450.80	4897.86	0.00	4510.65	3297.10	0.888
5	1.276	1.480	1728.00	89.31	2319.40	1265.63	1303.87	4888.89	0.00	5070.49	3427.02	0.863
6	1.340	1.600	2112.00	78.16	2935.02	949.22	1140.34	5024.58	0.00	5686.11	3553.50	0.837
7	1.407	1.731	2496.00	68.45	3608.44	711.91	958.32	5278.67	0.00	6359.53	3674.85	0.813
8	1.477	1.872	2880.00	59.69	4343.26	533.94	755.74	5632.93	0.00	7094.35	3790.53	0.789
9	1.551	2.024	3264.00	52.71	5145.30	400.45	530.26	6076.01	0.00	7896.39	3901.12	0.766
10	1.629	2.189	3648.00	47.11	6018.94	300.34	279.31	3482.79	0.00	4753.21	2171.31	0.744

Actual salvage value ($) = 4016.82
Mortgage payment ($) = 2751.09
Actual balancing chrge ($) = 3115.80

32914.68 / 8.530

Present annual cost ($) = 3858.61

Fuel cost ($) = 2359.21

Labour cost ($) = 5000.00

Shelter cost ($) = 160.00

APPENDIX A3

Annual ownership costs calculation for a 60 kW two-wheel drive tractor with an initial price of £16000.
Ownership period from 1 to 10 years taking into account 27% tax

Input data of: TR

Purchase price ($) = 16000.00 Used hours (h/yr) = 1000.00

Loan rate	= 0.1130	Interest rate	= 0.0815	Inflation rate	= 0.0500
Tax rate	= 0.27				
Fuel cost ($/L)=	0.13	Labour cost ($/h)=	5.00	Shelter	= 0.01

Repair coefficients:	Ar = 0.012		Br = 2.000
Resale coefficients:	As = 68.000		Bs = 0.920
Resale coefficients:	k1 = 0.237		k2 = 0.005

Output cost data : TR

Age	Inflation factor	Investment factor	Repair cost	Insurance	Actual repair & insurance	Actual capital allowance	Actual interest charge	Total tax allowance	Total tax relief	Actual cash outgoing	Discount cash flow	Inflated discount factor
Yr			$	$	$	$	$	$	$	$	$	%
1	1.050	1.082	192.00	176.50	386.93	4000.00	1808.00	4873.43	1315.83	3557.60	3289.50	0.971

Actual salvage value ($) = 13321.49
Mortgage payment ($) = 17807.99
Actual balancing chrge ($) = 1321.49

3289.50 / 0.971

Present annual cost ($) = 3388.19

Fuel cost ($) = 2359.21

Labour cost ($) = 5000.00

Shelter cost ($) = 160.00

Input data of: TR

Purchase price ($) = 16000.00 Used hours (h/yr) = 1000.00

Loan rate = 0.1130 Interest rate = 0.0815 Inflation rate = 0.0500
Tax rate = 0.27

Fuel cost ($/L)= 0.13 Labour cost ($/h)= 5.00 Shelter = 0.01

Repair coefficients: Ar = 0.012 Br = 2.000
Resale coefficients: As = 68.000 Bs = 0.920
Resale coefficients: k1 = 0.237 k2 = 0.005

Output cost data : TR

Age Yr	Infla-tion factor	Invest-ment factor	Repair cost $	Insur-ance $	Actual repair & insuran-ce $	Actual capital allow-ance $	Actual interest charge $	Total tax allow-ance $	Total tax relief $	Actual cash outgoing $	Discount cash flow $	Inflated discount factor %
1	1.050	1.082	192.00	176.50	386.93	4000.00	1808.00	6194.92	1672.63	8094.46	7484.48	0.971
2	1.102	1.170	576.00	146.03	796.04	3000.00	952.34	2545.52	687.29	-1713.94	-1465.36	0.943

Actual salvage value ($) = 11202.86
Mortgage payment ($) = 9380.17
Actual balancing chrge ($) = 2202.86

6019.12 / 1.913

Present annual cost ($) = 3145.66

Fuel cost ($) = 2359.21

Labour cost ($) = 5000.00

Shelter cost ($) = 160.00

Input data of: TR

Purchase price ($) = 16000.00 Used hours (h/yr) = 1000.00

Loan rate	= 0.1130	Interest rate	= 0.0815	Inflation rate	= 0.0500
Tax rate	= 0.27				
Fuel cost ($/L) =	0.13	Labour cost ($/h) =	5.00	Shelter	= 0.01

Repair coefficients:	Ar	= 0.012	Br	= 2.000
Resale coefficients:	As	= 68.000	Bs	= 0.920
Resale coefficients:	k1	= 0.237	k2	= 0.005

Output cost data : TR

Age Yr	Inflation factor	Investment factor	Repair cost $	Insurance $	Actual repair & insurance $	Actual capital allowance $	Actual interest charge $	Total tax allowance $	Total tax relief $	Actual cash outgoing $	Discount cash flow $	Inflated discount factor %
1	1.050	1.082	192.00	170.50	386.93	4000.00	1808.00	5194.92	1672.63	5295.89	4896.80	0.971
2	1.102	1.170	576.00	146.03	796.04	3000.00	1268.58	5064.62	1367.45	6010.19	5138.48	0.943
3	1.158	1.265	960.00	122.03	1252.59	2250.00	668.21	1404.95	379.34	-2061.00	-1629.29	0.915

Actual salvage value ($) = 9515.85
Mortgage payment ($) = 6581.60
Actual balancing chrge ($) = 2765.85

8405.99 / 2.829

Present annual cost ($) = 2971.77

Fuel cost ($) = 2359.21

Labour cost ($) = 5000.00

Shelter cost ($) = 160.00

Input data of: TR

Purchase price ($) = 16000.00 Used hours (h/yr) = 1000.00

Loan rate = 0.1130 Interest rate = 0.0815 Inflation rate = 0.0500
Tax rate = 0.27

Fuel cost ($/L)= 0.13 Labour cost ($/h)= 5.00 Shelter = 0.01

Repair coefficients: Ar = 0.012 Br = 2.000
Resale coefficients: As = 68.000 Bs = 0.920
Resale coefficients: k1 = 0.237 k2 = 0.005

Output cost data : TR

Age Yr	Inflation factor	Investment factor	Repair cost $	Insurance $	Actual repair & insurance $	Actual capital allowance $	Actual interest charge $	Total tax allowance $	Total tax relief $	Actual cash outgoing $	Discount cash flow $	Inflated discount factor %
1	1.050	1.082	192.00	176.50	386.93	4000.00	1608.00	6194.92	1672.63	3904.59	3610.34	0.971
2	1.102	1.170	576.00	146.03	796.04	3000.00	1425.80	5221.84	1409.90	4576.43	3912.68	0.943
3	1.158	1.265	960.00	122.03	1252.59	2250.00	1000.41	4503.00	1215.81	5227.07	4132.17	0.915
4	1.216	1.368	1344.00	103.59	1759.56	1687.50	526.96	872.39	235.55	-1449.82	-1059.76	0.868

Actual salvage value ($) = 8164.12 10595.43 / 3.717
Mortgage payment ($) = 5190.29
Actual balancing chrge ($) = 3101.62

Present annual cost ($) = 2850.46

Fuel cost ($) = 2359.21

Labour cost ($) = 5000.00

Shelter cost ($) = 160.00

Input data of: TR

Purchase price ($) = 16000.00   Used hours (h/yr) = 1000.00

Loan rate = 0.1130   Interest rate = 0.0815   Inflation rate = 0.0500
Tax rate = 0.27

Fuel cost ($/L)= 0.13   Labour cost ($/h)= 5.00   Shelter = 0.01

Repair coefficients: Ar = 0.012   Br = 2.000
Resale coefficients: As = 68.000   Bs = 0.920
Resale coefficients: k1 = 0.237   k2 = 0.005

Output cost data : TR

Age Yr	Inflation factor	Investment factor	Repair cost $	Insurance $	Actual repair & insurance $	Actual capital allowance $	Actual interest charge $	Total tax allowance $	Total tax relief $	Actual cash outgoing $	Discount cash flow $	Inflated discount factor %
1	1.050	1.082	192.00	176.50	380.93	4000.00	1808.00	5194.92	1672.63	3076.14	2844.32	0.971
2	1.102	1.170	576.00	140.03	796.04	3000.00	1519.42	5315.45	1435.17	3722.71	3182.77	0.943
3	1.158	1.265	960.00	122.03	1252.59	2250.00	1198.22	4700.81	1269.22	4345.21	3435.04	0.915
4	1.216	1.368	1344.00	105.59	1759.56	1687.50	840.73	4287.79	1157.70	4963.70	3628.26	0.888
5	1.276	1.480	1728.00	89.31	2319.40	1265.63	442.85	749.94	202.48	-596.05	-402.85	0.863

Actual salvage value ($) = 7074.80
Mortgage payment ($) = 4361.84
Actual balancing chrge ($) = 3277.93

12687.54 / 4.580

Present annual cost ($) = 2770.38

Fuel cost ($) = 2359.21

Labour cost ($) = 5000.00

Shelter cost ($) = 160.00

Input data of: TR

Purchase price ($) = 16000.00   Used hours (h/yr) = 1000.00

Loan rate = 0.1130   Interest rate = 0.0815   Inflation rate = 0.0500
Tax rate = 0.27

Fuel cost ($/l)= 0.13   Labour cost ($/h)= 5.00   Shelter = 0.01

Repair coefficients: Ar = 0.012   Br = 2.000
Resale coefficients: As = 68.000   Bs = 0.920
Resale coefficients: k1 = 0.237   k2 = 0.005

Output cost data : TR

Age	Infla-tion factor	Invest-ment factor	Repair cost	Insur-ance	Actual repair & insurance	Actual capital allow-ance	Actual interest charge	Total tax allow-ance	Total tax relief	Actual cash outgoing	Discount cash flow	Inflated discount factor
Yr			$	$	$	$	$	$	$	$	$	%
1	1.050	1.082	192.00	176.50	386.93	4000.00	1808.00	5194.92	1072.63	2529.06	2338.48	0.971
2	1.102	1.170	576.00	146.03	796.04	3000.00	1581.24	5377.27	1451.86	3158.94	2700.77	0.943
3	1.158	1.265	960.00	122.03	1252.59	2250.00	1328.85	4831.43	1304.49	3762.87	2974.67	0.915
4	1.216	1.368	1344.00	103.59	1759.56	1687.50	1047.94	4494.99	1213.65	4360.68	3187.48	0.888
5	1.276	1.480	1728.00	89.31	2319.40	1265.63	735.28	4320.31	1166.48	4967.68	3357.54	0.863
6	1.340	1.600	2112.00	78.16	2935.02	949.22	387.30	926.76	250.23	307.13	191.94	0.837

Actual salvage value ($) = 6192.44   14750.88 / 5.417
Mortgage payment ($) = 3814.77
Actual balancing chrge ($) = 3344.79

Present annual cost ($) = 2722.98

Fuel cost ($) = 2359.21

Labour cost ($) = 5000.00

Shelter cost ($) = 160.00

Input data of: TR

Purchase price ($) = 16000.00 Used hours (h/yr) = 1000.00

Loan rate = 0.1130 Interest rate = 0.0815 Inflation rate = 0.0500
Tax rate = 0.27

Fuel cost ($/l)= 0.13 Labour cost ($/h)= 5.00 Shelter = 0.01

Repair coefficients: Ar = 0.012 Br = 2.000
Resale coefficients: As = 68.000 Bs = 0.920
Resale coefficients: k1 = 0.237 k2 = 0.005

Output cost data : TR

Age Yr	Inflation factor	Investment factor	Repair cost $	Insurance $	Actual repair & insurance $	Actual capital allowance $	Actual interest charge $	Total tax allowance $	Total tax relief $	Actual cash outgoing $	Discount cash flow $	Inflated discount factor %
1	1.050	1.082	192.00	176.50	386.93	4000.00	1808.00	6194.92	1672.63	2142.72	1981.24	0.971
2	1.102	1.170	576.00	146.03	796.04	3000.00	1624.89	5420.93	1463.65	2760.81	2560.38	0.943
3	1.158	1.265	960.00	122.03	1252.59	2250.00	1421.09	4923.68	1329.39	3351.61	2649.56	0.915
4	1.216	1.368	1344.00	103.59	1759.56	1687.50	1194.27	4641.32	1253.16	3934.82	2876.20	0.888
5	1.276	1.480	1728.00	89.31	2319.40	1265.63	941.81	4526.83	1222.24	4525.57	3058.73	0.863
6	1.340	1.630	2112.00	78.16	2935.02	949.22	660.82	4545.06	1227.17	5136.28	3209.88	0.837
7	1.407	1.731	2496.00	68.45	3608.44	711.91	348.08	1329.57	358.98	1203.27	695.31	0.813

Actual salvage value ($) = 5474.60
Mortgage payment ($) = 3428.42
Actual balancing chrge ($) = 3338.86

16831.32 / 6.230

Present annual cost ($) = 2701.53

Fuel cost ($) = 2359.21

Labour cost ($) = 5000.00

Shelter cost ($) = 160.00

Input data of: TR

Purchase price ($) = 16000.00 Used hours (h/yr) = 1000.00

Loan rate = 0.1130 Interest rate = 0.0815 Inflation rate = 0.0500
Tax rate = 0.27

Fuel cost ($/L)= 0.13 Labour cost ($/h)= 5.00 Shelter = 0.01

Repair coefficients: Ar = 0.012 Br = 2.000
Resale coefficients: As = 68.000 Bs = 0.920
Resale coefficients: k1 = 0.237 k2 = 0.005

Output cost data : TR

Age Yr	Inflation factor	Investment factor	Repair cost $	Insurance $	Actual repair & insurance $	Actual capital allowance $	Actual interest charge $	Total tax allowance $	Total tax relief $	Actual cash outgoing $	Discount cash flow $	Inflated discount factor %
1	1.050	1.082	192.00	176.50	386.93	4000.00	1808.00	6194.92	1672.63	1856.77	1716.85	0.971
2	1.102	1.170	576.00	146.03	796.04	3000.00	1657.20	5453.24	1472.37	2466.14	2108.45	0.943
3	1.158	1.265	960.00	122.03	1252.59	2250.00	1489.37	4991.96	1347.83	3047.23	2408.94	0.915
4	1.216	1.368	1344.00	103.59	1759.56	1687.50	1302.57	4749.62	1282.40	3619.63	2645.81	0.888
5	1.276	1.480	1728.00	89.31	2319.40	1265.63	1094.66	4679.68	1263.51	4198.36	2837.57	0.863
6	1.340	1.600	2112.00	78.16	2935.02	949.22	863.25	4747.50	1281.82	4795.68	2997.03	0.837
7	1.407	1.731	2496.00	68.45	3608.44	711.91	605.70	4926.06	1330.03	5420.88	3132.45	0.813
8	1.477	1.872	2880.00	59.69	4343.26	533.94	319.05	1909.43	515.55	2081.57	1112.19	0.789

18959.29 / 7.020

Actual salvage value ($) = 4888.62
Mortgage payment ($) = 3142.48
Actual balancing chrge ($) = 3286.81

Present annual cost ($) = 2700.87

Fuel cost ($) = 2359.21

Labour cost ($) = 5000.00

Shelter cost ($) = 160.00

Input data of: TR

Purchase price ($) = 16000.00 Used hours (h/yr) = 1000.00

Loan rate = 0.1130 Interest rate = 0.0815 Inflation rate = 0.0500
Tax rate = 0.27

Fuel cost ($/L) = 0.13 Labour cost ($/h) = 5.00 Shelter = 0.01

Repair coefficients: Ar = 0.012 Br = 2.000
Resale coefficients: As = 68.000 Bs = 0.920
Resale coefficients: k1 = 0.237 k2 = 0.305

Output cost data : TR

Age	Inflation factor	Investment factor	Repair cost	Insurance	Actual repair & insurance	Actual capital allowance	Actual interest charge	Total tax allowance	Total tax relief	Actual cash outgoing	Discount cash flow	Inflated discount factor
Yr			$	$	$	$	$	$	$	$	$	%
1	1.050	1.082	192.00	176.50	386.93	4000.00	1808.00	5194.92	1672.63	1637.70	1514.29	0.971
2	1.102	1.170	576.00	146.03	796.04	3000.00	1681.96	5478.00	1479.06	2240.38	1915.44	0.943
3	1.158	1.265	960.00	122.03	1252.59	2250.00	1541.68	5044.26	1361.95	2814.04	2224.59	0.915
4	1.216	1.368	1344.00	103.59	1759.56	1687.50	1385.54	4832.60	1304.80	3378.16	2469.30	0.888
5	1.276	1.480	1728.00	89.31	2319.40	1265.63	1211.76	4796.78	1295.13	3947.67	2668.14	0.863
6	1.340	1.600	2112.00	78.16	2935.02	949.22	1018.35	4902.59	1323.70	4534.73	2833.95	0.837
7	1.407	1.731	2496.00	68.45	3608.44	711.91	803.07	5123.43	1383.33	5148.52	2975.06	0.813
8	1.477	1.872	2880.00	59.69	4343.26	533.94	563.48	5440.67	1468.98	5797.68	3097.72	0.769
9	1.551	2.024	3264.00	52.71	5145.30	400.45	296.81	2634.68	711.36	2948.11	1456.48	0.766

Actual salvage value ($) = 4409.23
Mortgage payment ($) = 2923.40
Actual balancing chrge ($) = 3207.87

21154.97 / 7.786

Present annual cost ($) = 2717.02

Fuel cost ($) = 2359.21

Labour cost ($) = 5000.00

Shelter cost ($) = 160.00

Input data of: TR

Purchase price ($) = 16000.00   Used hours (h/yr) = 1000.00

Loan rate = 0.1130   Interest rate = 0.0815   Inflation rate = 0.0500
Tax rate = 0.27

Fuel cost ($/L)= 0.13   Labour cost ($/h)= 5.00   Shelter = 0.01

Repair coefficients: Ar = 0.012   Br = 2.000
Resale coefficients: As = 68.000   Bs = 0.920
Resale coefficients: k1 = 0.237   k2 = 0.005

Output cost data : TR

Age Yr	Inflation factor	Investment factor	Repair cost $	Insurance $	Actual repair & insurance $	Actual capital allowance $	Actual interest charge $	Total tax allowance $	Total tax relief $	Actual cash outgoing $	Discount cash flow $	Inflated discount factor %
1	1.050	1.082	192.00	176.50	386.93	4000.00	1808.00	5194.92	1672.63	1465.38	1354.96	0.971
2	1.102	1.170	576.00	146.03	796.04	3000.00	1701.43	5497.47	1484.32	2062.81	1763.62	0.943
3	1.158	1.265	960.00	122.03	1252.59	2250.00	1582.82	5085.41	1373.06	2630.62	2079.59	0.915
4	1.216	1.368	1344.00	103.59	1759.56	1687.50	1450.80	4897.86	1322.42	3188.22	2330.47	0.888
5	1.276	1.480	1728.00	89.31	2319.40	1265.63	1303.87	4888.89	1320.00	3750.48	2534.86	0.863
6	1.340	1.600	2112.00	78.16	2935.02	949.22	1140.34	5024.58	1356.64	4329.48	2705.68	0.837
7	1.407	1.731	2496.00	68.45	3608.44	711.91	958.32	5278.67	1425.24	4934.29	2851.27	0.813
8	1.477	1.872	2880.00	59.69	4343.26	533.94	755.74	5632.93	1520.89	5573.46	2977.91	0.789
9	1.551	2.024	3264.00	52.71	5145.30	400.45	530.26	6076.01	1640.52	6255.86	3090.64	0.766
10	1.629	2.189	3648.00	47.11	6018.94	300.34	279.31	3482.79	940.35	3812.86	1741.75	0.744

23430.75 / 8.530

Actual salvage value ($) = 4016.82
Mortgage payment ($) = 2751.09
Actual balancing chrge ($) = 3115.80

Present annual cost ($) = 2746.80

Fuel cost ($) = 2359.21

Labour cost ($) = 5000.00

Shelter cost ($) = 160.00

APPENDIX B

Tractor/plough performance model

```
c       INPUT DATA FOR TWO WHEEL DRIVE TRACTOR
c       ______________________________________
c
c       Open data file.
c
        OPEN(UNIT=LUDA,NAME='MSA01.DAT',TYPE='UNKNOWN',DISPOSE='SAVE',
       &     ACCESS='DIRECT',CARRIAGECONTROL='NONE',FORM='UNFORMATTED',
       &     RECORDSIZE=A01RL,ASSOCIATEVARIABLE=NDAR,MAXREC=MAXA01)
c
        WRITE(LUTT,10)
        WRITE(LUTT,20)
   10   FORMAT(1H0,'  2-WHEEL DRIVE              ')
   20   FORMAT(1H ,'  -----------------------')
c
c       Record number.
c       Units: none.
c
c       Prevent record number 0 being selected.
        IF (A01REC.EQ.0) A01REC= 1
   30   CALL LINE(LUTT)
        WRITE(LUTT,40)
   40   FORMAT(1H ,'  tractor number           ',$)
        CALL PGI(LUTT,LUTT,5,A01REC,4,11,1,MAXA01,ERROR)
        IF (ERROR.NE.0) GOTO 30
c
c       Read data from file.
c
        READ(LUDA'A01REC) TNAME,RWLD,TRW,RMD,TINFP,FTW,FRD,FINFP,
       &                  FLDD,WBAS,NOGRS,PS,ENTQ,ENSP
c
c       Model/manufacturer.
c       Units: none
c
   50   CALL LINE(LUTT)
        WRITE(LUTT,60)
   60   FORMAT(1H ,'  manufacturer/model       ',$)
        CALL PGT(LUTT,LUTT,2,TNAME,4,2)
c
c       Rear load on rear wheels.
c       Units: kg.
c
   70   CALL LINE(LUTT)
        WRITE(LUTT,80)
   80   FORMAT(1H ,'  load on rear wheels (kg)',$)
        CALL PGR(LUTT,LUTT,2,RWLD,10.2,8,100.00,10000.00,ERROR)
        IF (ERROR.NE.0) GOTO 70
c
c       Rear tyre width.
c       Units: inches.
c
   90   WRITE(LUTT,100)
  100   FORMAT(1H ,'  rear wheel width    (in)',$)
        CALL PGR(LUTT,LUTT,2,TRW,10.2,8,5.20,50.40,ERROR)
        IF (ERROR.NE.0) GOTO 90
c
c       Rear rim diameter.
c       Units: inches.
c
  110   WRITE(LUTT,120)
  120   FORMAT(1H ,'  rear rim diameter   (in)',$)
        CALL PGR(LUTT,LUTT,2,RMD,10.2,8,10.00,100.00,ERROR)
```

```
      IF (ERROR.NE.0) GOTO 110
c
c     Rear tyre inflation pressure.
c     Units: kPa.
c
  130 WRITE(LUTT,140)
  140 FORMAT(1H ,'  rear tyre pressure (kPa)',$)
      CALL PGR(LUTT,LUTT,2,TINFP,10.2,8,10.00,500.00,ERROR)
      IF (ERROR.NE.0) GOTO 130
c
c     Front tyre section width.
c     Units: inches.
c
  150 CALL LINE(LUTT)
      WRITE(LUTT,160)
  160 FORMAT(1H ,'  front tyre width    (in)',$)
      CALL PGR(LUTT,LUTT,2,FTW,10.2,8,2.00,50.40,ERROR)
      IF (ERROR.NE.0) GOTO 150
c
c     Front rim dimeter.
c     Units: inches.
c
  170 WRITE(LUTT,180)
  180 FORMAT(1H ,'  front rim diameter  (in)',$)
      CALL PGR(LUTT,LUTT,2,FRD,10.2,8,5.00,100.00,ERROR)
      IF (ERROR.NE.0) GOTO 170
c
c     Front tyre inflation pressure.
c     Units: kPa.
c
  190 WRITE(LUTT,200)
  200 FORMAT(1H ,'  front tyre pressure(kPa)',$)
      CALL PGR(LUTT,LUTT,2,FINFP,10.2,8,10.00,500.00,ERROR)
      IF (ERROR.NE.0) GOTO 190
c
c     Front tyre static load distribution.
c     Units: %.
  210 WRITE(LUTT,220)
  220 FORMAT(1H ,'  front static load    (%)',$)
      CALL PGR(LUTT,LUTT,2,FLDD,10.2,8,10.00,90.00,ERROR)
      IF (ERROR.NE.0) GOTO 210
c
c     Wheelbase
c     Units: m.
c
  230 WRITE(LUTT,240)
  240 FORMAT(1H ,'  wheelbase             (m)',$)
      CALL PGR(LUTT,LUTT,2,WBAS,10.2,8,1.50,3.50,ERROR)
      IF (ERROR.NE.0) GOTO 230
c
c     Number of gears.
c     Units:none.
c
  250 CALL LINE(LUTT)
      WRITE(LUTT,260)
  260 FORMAT(1H ,'  number of gears          ',$)
      CALL PGI(LUTT,LUTT,5,NOGRS,4,11,1,9,ERROR)
      IF (ERROR.NE.0) GOTO 250
c
  270 CALL LINE(LUTT)
      DO 132 I = 1,NOGRS
      WRITE(LUTT,280) I
  280 FORMAT(1H ,'  speed in gear',I1,'    (km/h)',$)
      CALL PGR(LUTT,LUTT,2,PS(I),10.2,8,1.00,50.00,ERROR)
```

```
      IF (ERROR.NE.0) GOTO 270
  132 CONTINUE
c
c      Engine torque at the maximum power.
c      Units: Nm.
c
  390 CALL LINE(LUTT)
      WRITE(LUTT,400)
  400 FORMAT(1H ,'  eng.torque at max.  (Nm)',$)
      CALL PGR(LUTT,LUTT,2,ENTQ,10.2,8,10.00,900.00,ERROR)
      IF(ERROR.NE.0) GOTO 390
c
  410 WRITE(LUTT,420)
  420 FORMAT(1H ,'  eng.speed at max.(re/mn)',$)
      CALL PGI(LUTT,LUTT,5,ENSP,4,11,100,10000,ERROR)
      IF(ERROR.NE.0) GOTO 410
c
c     Write data to file.
c
      DO 500 A01REC=1,MAXA01
      WRITE(LUDA'A01REC) TNAME,RWLD,TRW,RMD,TINFP,FTW,FRD,FINFP,
     &                   FLDD,WBAS,NOGRS,PS,ENTQ,ENSP
  500 CONTINUE

c     Close data file.
c
      CLOSE(UNIT=LUDA)
c
      RETURN
c
      END
```

```
c
c     INPUT DATA FOR MOULDBOARD PLOUGH
      ______________________________________
c
c     Open data file.
c
      OPEN(UNIT=LUDA,NAME='MSC01.DAT',TYPE='OLD',DISPOSE='SAVE',
     &     ACCESS='DIRECT',CARRIAGECONTROL='NONE',FORM='UNFORMATTED',
     &     RECORDSIZE=C01RL,ASSOCIATEVARIABLE=NDAR,MAXREC=MAXC01)
c
      WRITE(LUTT,10)
      WRITE(LUTT,20)
   10 FORMAT(1H0,'  MOULD BOARD                ')
   20 FORMAT(1H ,'  -----------------------')
c
c     Prevent record number 0 being selected.
      IF (C01REC.EQ.0) C01REC= 1
   30 CALL LINE(LUTT)
      WRITE(LUTT,40)
   40 FORMAT(1H ,'  plough number              ',$)
      CALL PGI(LUTT,LUTT,5,C01REC,4,11,1,MAXC01,ERROR)
      IF (ERROR.NE.0) GOTO 30
c
c     Read data from file.
c
      READ(LUDA'C01REC) MINPBS,MAXPBS,PANGLE
c
  180 CALL LINE(LUTT)
      WRITE(LUTT,190)
  190 FORMAT(1H ,'  min plough bodies        ',$)
      CALL PGI(LUTT,LUTT,5,MINPBS,4,11,1,10,ERROR)
      IF (ERROR.NE.0) GOTO 180
c
  195 WRITE(LUTT,198)
  198 FORMAT(1H ,'  max plough bodies        ',$)
      CALL PGI(LUTT,LUTT,5,MAXPBS,4,11,1,10,ERROR)
      IF (ERROR.NE.0) GOTO 195
c
  200 CALL LINE(LUTT)
      WRITE(LUTT,210)
  210 FORMAT(1H ,'  plough tail angle  (rad)',$)
      CALL PGR(LUTT,LUTT,2,PANGLE,10.2,8,0.50,0.95,ERROR)
      IF (ERROR.NE.0) GOTO 200
c
c
c
c     Write data to file.
c
      WRITE(LUDA'C01REC) MINPBS,MAXPBS,PANGLE
c
c     Close data file.
c
      CLOSE(UNIT=LUDA)
c
      RETURN
c
      END
```

```
c
c      INPUT DATA FOR SOIL SPECIFICATIONS
c      __________________________________
c
c      Open data file.
c
       OPEN(UNIT=LUDA,NAME='MSSS.DAT',TYPE='OLD',DISPOSE='SAVE',
     &      ACCESS='DIRECT',CARRIAGECONTROL='NONE',FORM='UNFORMATTED',
     &      RECORDSIZE=SSRL,ASSOCIATEVARIABLE=NDAR,MAXREC=MAXSS)
c
       WRITE(LUTT,10)
       WRITE(LUTT,20)
    10 FORMAT(1H0,'  SOIL SPECIFICATIONS     ')
    20 FORMAT(1H ,'  -----------------------')
c
c      Prevent record number 0 being selected.
       IF (SSREC.EQ.0) SSREC = 1
    25 CALL LINE(LUTT)
       WRITE(LUTT,28)
    28 FORMAT(1H ,'  soil number               ',$)
       CALL PGI(LUTT,LUTT,5,SSREC,4,11,1,MAXSS,ERROR)
       IF (ERROR.NE.0) GOTO 25
c
c      Read data from file.
c
       READ(LUDA'SSREC) SSNAME,PCLAY,PSILT,PSAND,PHUMUS,FC,
     &                  MCWW,MCFC,SBD,DRSAT,DRFC,SLQWW,SLQFC,SPLWW,
     &                  SPLFC,SWPWW,SWPFC,WABY,SKC,SKF,SCR
c
    30 CALL LINE(LUTT)
       WRITE(LUTT,40)
    40 FORMAT(1H ,'  name          (1-16 chars)',$)
       CALL PGT(LUTT,LUTT,2,SSNAME,4,2)
       ERROR = 1
       IF (SSNAME(1).EQ.'WINT'.OR.SSNAME(1).EQ.'DARV'.OR.
     &    'MACM') ERROR = 0
       IF (ERROR.EQ.1) WRITE(LUTT,50)
c
    50 FORMAT(1H0,'  Valid soil series are Winton and Darvel and
     & Macmerry. ',/,
     &      '   Please correct your entry.',/)
       IF (ERROR.NE.0) GOTO 30
c
    60 CALL LINE(LUTT)
       WRITE(LUTT,70)
    70 FORMAT(1H ,'  clay                     (%)',$)
       CALL PGR(LUTT,LUTT,2,PCLAY,10.2,8,0.00,100.00,ERROR)
       IF (ERROR.NE.0) GOTO 60
C
    80 WRITE(LUTT,90)
    90 FORMAT(1H ,'  silt                     (%)',$)
       CALL PGR(LUTT,LUTT,2,PSILT,10.2,8,0.00,50.00,ERROR)
       IF (ERROR.NE.0) GOTO 80
c
   100 WRITE(LUTT,110)
   110 FORMAT(1H ,'  sand                     (%)',$)
       CALL PGR(LUTT,LUTT,2,PSAND,10.2,8,0.00,100.00,ERROR)
       IF (ERROR.NE.0) GOTO 100
c
   120 WRITE(LUTT,130)
   130 FORMAT(1H ,'  humus                    (%)',$)
       CALL PGR(LUTT,LUTT,2,PHUMUS,10.2,8,0.00,50.00,ERROR)
```

```
      WRITE(LUTT,370)
  370 FORMAT(1H ,'  wilting point      (%w/w)',$)
      CALL PGR(LUTT,LUTT,2,SWPWW,10.2,8,1.00,100.00,ERROR)
      IF (ERROR.NE.0) GOTO 360
  380 WRITE(LUTT,390)
  390 FORMAT(1H ,'  wilting point      (%fc)',$)
      CALL PGR(LUTT,LUTT,2,SWPFC,10.2,8,1.00,100.00,ERROR)
      IF (ERROR.NE.0) GOTO 380
c
  400 WRITE(LUTT,410)
  410 FORMAT(1H ,'  soil workability   (%fc)',$)
      CALL PGI(LUTT,LUTT,5,WABY,4,11,100,110,ERROR)
      IF (ERROR.NE.0) GOTO 400
c
c       IF (WABY.EQ. 90) GOTO 430
c       IF (WABY.EQ. 95) GOTO 430
      IF (WABY.EQ.100) GOTO 430
      IF (WABY.EQ.105) GOTO 430
      IF (WABY.EQ.110) GOTO 430
c       IF (WABY.EQ.115) GOTO 430
c       IF (WABY.EQ.120) GOTO 430
c       IF (WABY.EQ.125) GOTO 430
c       IF (WABY.EQ.130) GOTO 430
c
      WRITE(LUTT,420)
  420 FORMAT(1H0,'  Valid values for soil workability are ',/,
     &         '  100, 105, and 110.',/,
     &         '  Please correct your entry.',/)
      GOTO 400
  430 CONTINUE
c
  440 CALL LINE(LUTT)
      WRITE(LUTT,450)
  450 FORMAT(1H ,'  cohesive parameter       ',$)
      CALL PGR(LUTT,LUTT,2,SKC,13.5,5,0.00001,100.00000,ERROR)
      IF (ERROR.NE.0) GOTO 440
c
  470 WRITE(LUTT,480)
  480 FORMAT(1H ,'  frictional parameter     ',$)
      CALL PGR(LUTT,LUTT,2,SKF,13.5,5,0.00001,100.10000,ERROR)
      IF (ERROR.NE.0) GOTO 470
c
  490 WRITE(LUTT,500)
  500 FORMAT(1H ,'  soil clay ratio          ',$)
      CALL PGR( LUTT,LUTT,2,SCR,12.4,6,0.0010,100.0000,ERROR)
      IF (ERROR.NE.0) GOTO 490
c
c     Write data to file.
c
      WRITE(LUDA'SSREC) SSNAME,PCLAY,PSILT,PSAND,PHUMUS,FC,
     &                  MCWW,MCFC,SBD,DRSAT,DRFC,SLQWW,SLQFC,SPLWW,
     &                  SPLFC,SWPWW,SWPFC,WABY,SKC,SKF,SCR
c
c     Close data file.
c
      CLOSE(UNIT=LUDA)
c
      RETURN
C
      END
```

```
c       INPUT DATA FOR OPERATING CONDITIONS
c       ------------------------------------
c
c
c       Open data file.
c
        OPEN(UNIT=LUDA,NAME='MSOC.DAT',TYPE='OLD',DISPOSE='SAVE',
     &      ACCESS='DIRECT',CARRIAGECONTROL='NONE',FORM='UNFORMATTED',
     &      RECORDSIZE=OCRL,ASSOCIATEVARIABLE=NDAR,MAXREC=MAXOC)
c
        WRITE(LUTT,10)
        WRITE(LUTT,20)
   10 FORMAT(1H0,'  OPERATING CONDITIONS    ')
   20 FORMAT(1H ,'  -----------------------')
c
c       Prevent record number 0 being selected.
        IF (OCREC.EQ.0) OCREC = 1
   30 CALL LINE(LUTT)
        WRITE(LUTT,40)
   40 FORMAT(1H ,'  operating number          ',$)
        CALL PGI(LUTT,LUTT,5,OCREC,4,11,1,MAXOC,ERROR)
        IF (ERROR.NE.0) GOTO 30
c
c       Read data from file.
c
        READ(LUDA'OCREC) SWNO,CWNO,FE,PROB,AREA,
     &                   MINPCD,MAXPCD,INCPCD,PLSDAY,PLCDAY,TTUSEH,
     &                   CROPNE
c
   50 CALL LINE(LUTT)
        WRITE(LUTT,60)
   60 FORMAT(1H ,'  start week number         ',$)
        CALL PGI(LUTT,LUTT,5,SWNO,4,11,1,52,ERROR)
        IF (ERROR.NE.0) GOTO 50
c
   70 WRITE(LUTT,80)
   80 FORMAT(1H ,'  finish week number        ',$)
        CALL PGI(LUTT,LUTT,5,CWNO,4,11,SWNO,52,ERROR)
        IF (ERROR.NE.0) GOTO 70
c
   90 CALL LINE(LUTT)
        WRITE(LUTT,100)
  100 FORMAT(1H ,'  field efficiency     (%)',$)
        CALL PGI(LUTT,LUTT,5,FE,4,11,60,100,ERROR)
        IF (ERROR.NE.0) GOTO 90
c
  110 CALL LINE(LUTT)
        WRITE(LUTT,120)
  120 FORMAT(1H ,'  probability level    (%)',$)
        CALL PGI(LUTT,LUTT,5,PROB,4,11,80,100,ERROR)
        IF (ERROR.NE.0) GOTO 110
c
c        IF (PROB.EQ. 70) GOTO 130
        IF (PROB.EQ. 80) GOTO 130
        IF (PROB.EQ. 90) GOTO 130
        IF (PROB.EQ.100) GOTO 130
c
        WRITE(LUTT,170)
  170 FORMAT(1H0,'  Valid values for probability level are ',/,
     &       '  80, 90 and 100.',/,
     &       '  Please correct your entry.',/)
        GOTO 110
```

```
  130 CONTINUE
c
  180 CALL LINE(LUTT)
      WRITE(LUTT,190)
  190 FORMAT(1H ,'  area                   (ha)',$)
      CALL PGR(LUTT,LUTT,2,AREA,10.2,8,100.00,1000.00,ERROR)
      IF (ERROR.NE.0) GOTO 180
c
  200 CALL LINE(LUTT)
C       WRITE(LURT,210)
C  210 FORMAT(1H ,'  min plough speed  (km/h)',$)
C       CALL PGR(LUTT,LUTT,2,MINPS,10.2,8,1.00,20.00,ERROR)
C       IF (ERROR.NE.0) GOTO 200
c
C  220 WRITE(LUTT,230)
C  230 FORMAT(1H ,'  max plough speed  (km/h)',$)
C       CALL PGR(LUTT,LUTT,2,MAXPS,10.2,8,1.00,20.00,ERROR)
C       IF (ERROR.NE.0) GOTO 220
c
C  240 WRITE(LUTT,250)
C  250 FORMAT(1H ,'  inc plough speed  (km/h)',$)
C       CALL PGR(LUTT,LUTT,2,INCPS,10.2,8,0.00,MAXPS,ERROR)
C       IF (ERROR.NE.0) GOTO 240
c
  260 CALL LINE(LUTT)
      WRITE(LUTT,270)
  270 FORMAT(1H ,'  min plough cut depth (m)',$)
      CALL PGR(LUTT,LUTT,2,MINPCD,10.2,8,0.05,0.40,ERROR)
      IF (ERROR.NE.0) GOTO 260
c
  280 WRITE(LUTT,290)
  290 FORMAT(1H ,'  max plough cut depth (m)',$)
      CALL PGR(LUTT,LUTT,2,MAXPCD,10.2,8,0.05,0.40,ERROR)
      IF (ERROR.NE.0) GOTO 280
c
  300 WRITE(LUTT,310)
  310 FORMAT(1H ,'  inc plough cut depth (m)',$)
      CALL PGR(LUTT,LUTT,2,INCPCD,10.2,8,0.05,0.40,ERROR)
      IF (ERROR.NE.0) GOTO 300
c
  340 CALL LINE(LUTT)
      WRITE(LUTT,350)
  350 FORMAT(1H ,'  plough start day        ',$)
      CALL PGI(LUTT,LUTT,5,PLSDAY,4,11,1,500,ERROR)
      IF (ERROR.NE.0) GOTO 340
c
  360 WRITE(LUTT,370)
  370 FORMAT(1H ,'  plough finish day       ',$)
      CALL PGI(LUTT,LUTT,5,PLCDAY,4,11,PLSDAY,500,ERROR)
      IF (ERROR.NE.0) GOTO 360

c     Tractor annual use.
c     Units: hours.
c
  380 CALL LINE(LUTT)
      WRITE(LUTT,390)
  390 FORMAT(1H ,'  tractor annual use (h/y)',$)
      CALL PGR(LUTT,LUTT,2,TTUSEH,10.2,8,0.00,12000.00,ERROR)
      IF (ERROR.NE.0) GOTO 380
c
  400 CALL LINE(LUTT)
      WRITE(LUTT,410)
  410 FORMAT(1H ,'    crop      (1-16 chars)',$)
      CALL PGT(LUTT,LUTT,2,CROPNE,4,2)
```

```
      ERROR = 1
      IF (CROPNE(1).EQ.'WWHE'.OR.CROPNE(1).EQ.'WBAR'.OR.CROPNE(1)
     &   .EQ.'SWHE'.OR.CROPNE(1).EQ.'SBAR'.OR.CROPNE(1).EQ.'AOTS'
     &   .OR.CROPNE(1).EQ.'POTA'.OR.CROPNE(1).EQ.'TURN'.OR.
     &   CROPNE(1).EQ.'SWED') ERROR = 0
      IF (ERROR.EQ.1) WRITE(LUTT,440)
  440 FORMAT(1H0,'  Valid crops are wwheat,wbarley,swheat,sbarley,
     & oats,potatoes,Turnips,and Swedes.',/,
     &          'Please correct your entry .',/)
      IF (ERROR.NE.0) GOTO 400
c     Write data to file.
c
      WRITE(LUDA'OCREC) SWNO,CWNO,FE,PROB,AREA,
     &                  MINPCD,MAXPCD,INCPCD,PLSDAY,PLCDAY,TTUSEH,
     &                  CROPNE
c
c     Close data file.
c
      CLOSE(UNIT=LUDA)
c
      RETURN
c
      END
```

```
c       INPUT DATA FOR SOIL WORKABILITY AND CROP DATA
c       _____________________________________________
c
c       Assign work days data.
c
c       Open data file.
c
        IF (PROB.EQ.080.AND.SSNAME(1).EQ.'WINT') GOTO 100
        IF (PROB.EQ.090.AND.SSNAME(1).EQ.'WINT') GOTO 110
        IF (PROB.EQ.100.AND.SSNAME(1).EQ.'WINT') GOTO 120
        IF (PROB.EQ.080.AND.SSNAME(1).EQ.'DARV') GOTO 200
        IF (PROB.EQ.090.AND.SSNAME(1).EQ.'DARV') GOTO 210
        IF (PROB.EQ.100.AND.SSNAME(1).EQ.'DARV') GOTO 220
        IF (PROB.EQ.080.AND.SSNAME(1).EQ.'MACM') GOTO 230
        IF (PROB.EQ.090.AND.SSNAME(1).EQ.'MACM') GOTO 240
        IF (PROB.EQ.100.AND.SSNAME(1).EQ.'MACM') GOTO 250
c
c       Winton soil series.
C?  100 WRITE(LUTT,501)
C?  501 FORMAT(1H0,'  THERE IS NO WORKABILITY 80% FOR WINTON SOIL')
c
        CALL EXIT
  100 FILNAM(1) = 'MS10'
        FILNAM(2) = '80.D'
        GOTO 1000
  110 FILNAM(1) = 'MS10'
        FILNAM(2) = '90.D'
        GOTO 1000
  120 FILNAM(1) = 'MS11'
        FILNAM(2) = '00.D'
        GOTO 1000
c
c       Darvel soil series.
c
  200 FILNAM(1) = 'MS20'
        FILNAM(2) = '80.D'
        GOTO 1000
  210 FILNAM(1) = 'MS20'
        FILNAM(2) = '90.D'
        GOTO 1000
  220 FILNAM(1) = 'MS21'
        FILNAM(2) = '00.D'
        GOTO 1000
c
c       Macmerry soil seies.
c
  230 FILNAM(1) = 'MS30'
        FILNAM(2) = '80.D'
        GOTO 1000
  240 FILNAM(1) = 'MS30'
        FILNAM(2) = '90.D'
        GOTO 1000
  250 FILNAM(1) = 'MS31'
        FILNAM(2) = '00.D'
        GOTO 1000
c
 1000 CONTINUE
c
        FILNAM(3) = 'AT  '
c
        OPEN(UNIT=LUDA,NAME=FILNAM,TYPE='OLD',DISPOSE='SAVE',
```

```
     &        ACCESS='SEQUENTIAL',FORM='FORMATTED')
c
c     Read work days data from file. Assign correct field to array.
c
      DO 1020 I=1,52
      READ(LUDA,1010) IFIELD(1),IFIELD(2),IFIELD(3),IFIELD(4)
 1010 FORMAT(I2,3(X,I1))
        IF (WABY.EQ.100) WDAYS(I) = IFIELD(2)
        IF (WABY.EQ.105) WDAYS(I) = IFIELD(3)
        IF (WABY.EQ.110) WDAYS(I) = IFIELD(4)
 1020 CONTINUE
c
c     Close data file.
c
      CLOSE(UNIT=LUDA)
c
      IF (CROPNE(1).EQ.'WWHE') GOTO 1071
      IF (CROPNE(1).EQ.'WBAR') GOTO 1072
      IF (CROPNE(1).EQ.'SWHE') GOTO 1073
      IF (CROPNE(1).EQ.'SBAR') GOTO 1074
      IF (CROPNE(1).EQ.'OATS') GOTO 1075
      IF (CROPNE(1).EQ.'POTA') GOTO 1076
      IF (CROPNE(1).EQ.'TURN') GOTO 1077
      IF (CROPNE(1).EQ.'SWED') GOTO 1078
c
      WRITE(LUTT,1111) CROPNE
 1111 FORMAT(1H ,'IN MSWDD CROP NAME IS ',4(A4))
 1071 OPTDN = 296
      MAXY  = 6.20
      CPA   = 0.00444
      CPB   = 0.00435
      GOTO 9000
c
c     Winter barley parameters.
c
 1072 OPTDN = 288
      MAXY  = 5.95
      CPA   = 0.00310
      CPB   = 0.00384
      GOTO 9000
c
c     Spring wheat parameters.
c
 1073 OPTDN = 76
      MAXY  = 3.83
      CPA   = 0.00878
      CPB   = 0.0109
      GOTO 9000
c
c     Spring barley parameters.
c
 1074 OPTDN = 76
      MAXY  = 4.88
      CPA   = 0.00911
      CPB   = 0.01102
      GOTO 9000
c
c     Oats parameters.
c
 1075 OPTDN = 81
      MAXY  = 4.92
      CPA   = 0.01346
      CPB   = 0.01941
      GOTO 9000
```

```
c
c     Potatoes parameters.
 1076 OPTDN = 104
      MAXY  = 42.21
      CPA   = 0.00581
      CPB   = 0.00913
      GOTO 9000
c
c      Turnips parameters.
 1077 OPTDN = 138
      MAXY  = 6.44
      CPA   = 0.04964
      CPB   = 0.03174
      GOTO 9000
c
c     Swedes parameters.
c
 1078 OPTDN = 125
      MAXY  = 5.27
      CPA   = 0.01722
      CPB   = 0.01843
      GOTO  9000
c
 9000 CONTINUE
c     Close data file.
c
c
      RETURN
c
      END
```

```
c
c
c
c         TECHNICAL CALCULATIONS
c       ____________________________
c
c
c         MATCHING SINGLE TRACTOR-IMPLEMENT COMBINATION
c       ______________________________________________________
c
c       Initialise variables.
        ID = 0
c
        RUNS =NA01RS*((MAXPBS-MINPBS)+1)*NOGRS
c
c       Acceleration due to gravity.
c       Units: m/s2.
c
        G = 9.807
c
c       Open data files.
c
        CALL MSOPEN
c
c       Read combination selection data.
c
        CSREC = 1
        READ(LUDA6'CSREC) NA01RS,A01R,A02R,A03R,A0R,NC01RS,C01R,
     &               NSSRS,TYPE,SSR,NOCRS,OCR,NACRS,ACR,NF01RS,F01R,
     &               NI00RS,I00R
c
        WRITE(LUTT,20) RUNS
   20 FORMAT(1H0,'  Comparing ',I4,' combinations. Please wait....',/)
c
        WRITE(LURT,40) TYPE
        WRITE(LURT,50)
        WRITE(LURT,60)
        WRITE(LURT,70)
        WRITE(LURT,80)
        WRITE(LURT,90)
        WRITE(LURT,97)
        WRITE(LURT,98)
        WRITE(LURT,100)
   40 FORMAT(1H ,'  2-WD tractor and plough specifications.
     &   ',4(A4),'  ')
   50 FORMAT(1H ,'  --------------------------------    ==========')
   60 FORMAT(1H0,  92('-'))
   70 FORMAT(1H ,'Tr.  Tyre dimensions     Tyre          tractor
     & load    Tractor  Plough       Engine      Engine')
   80 FORMAT(1H ,'      --------------        pressure       distribution
     &    used --------- ---------------')
   90 FORMAT(1H ,'      front      rear  ------------ ------------
     &---          Bod angle torque  speed   power')
   97 FORMAT(1H , 23X,'front  rear front front  rear',9x,'ies',10x,'at
     &maximum')
   98 FORMAT(1H ,'no.   (in)      (in)        (kPa)       (%)    (kN)
     & (kN) (h/yr)       (rad)  (Nm)  (rev/mn) (kW) ')
  100 FORMAT(1H , 92('-'))
c
c       Assign number of tractors for this run.
c
        DO 11 I = 1,NA01RS
        IF (TYPE.EQ.TWOWD) GOTO 9201
        IF (TYPE.EQ.UNE4 ) GOTO 9202
```

```
      IF (TYPE.EQ.EQ4W ) GOTO 9203
c
c     Read specific tractor type data.
c
 9201 IF (TYPE.EQ.TWOWD) AOR(I)=A01R(I)
      A01REC=A01R(I)
      READ(LUDA1'A01REC) TNAME,RWLD,TRW,RMD,TINFP,FTW,FRD,FINFP,
     &                   FLDD,WBAS,NOGRS,PS,ENTQ,ENSP
      GOTO 9204
 9202 IF (TYPE.EQ.UNE4 ) AOR(I)= A02R(I)
      A02REC=A02R(I)
      READ(LUDA9'A02REC) TNAME,RWLD,TRW,RMD,TINFP,FTW,FRM,FINFP,
     &                   FLDD,WBAS,NOGRS,PS,ENTQ,ENSP
      GOTO 9204
 9203 IF (TYPE.EQ.EQ4W ) AOR(I)= A03R(I)
      A03REC=A03R(I)
      READ(LUDA10'A03REC) TNAME,RWLD,TRW,RMD,TINFP,FTW,FRD,FINFP,
     &                    FLDD,WBAS,NOGRS,PS,ENTQ,ENSP
c
 9204 CONTINUE
      DO 88 J8 =1,NOGRS
c
c
c     Assign number of mould board ploughs for this run.
c
      DO 22 J1 =1,NC01RS
c
c     Read mould board plough data.
c
      C01REC = C01R(J1)
      READ(LUDA2'C01REC)  MINPBS,MAXPBS,PANGLE
c
c     Assign soil specification for this run.
c
      DO 33 K1 =1,NSSRS
c
c     Read soil specification data.
c
      SSREC = SSR(K1)
      READ(LUDA3'SSREC)  SSNAME,PCLAY,PSILT,PSAND,PHUMUS,FC,MCWW,
     &                   MCFC,SBD,DRSAT,DRFC,SLQWW,SLQFC,SPLWW,SPLFC,
     &                   SWPWW,SWPFC,WABY,SKC,SKF,SCR
c
c     Assign operating condition for this run.
c
      DO 44 L =1,NOCRS
c
c     Read operating condition data.
c
      OCREC = OCR(L)
      READ(LUDA4'OCREC)  SWNO,CWNO,FE,PROB,AREA,
     &                   MINPCD,MAXPCD,INCPCD,PLSDAY,PLCDAY,TTUSEH,
     &                   CROPNE
c
c     Assign work day data.
c
      CALL MSWDD
c
c
      MINPD = MINPCD*100.0
      MAXPD= MAXPCD*100.0
      INCPD= INCPCD*100.0
c
      DO 66 IIII1= MINPD,MAXPD,INCPD
```

```
         PCD = IIII1/100.0
         PCW = PCD + 0.05
      DO 77 KBB = MINPBS,MAXPBS,1
         PBS = KBB
c
      IDDD = IDDD + 1
c
c     Calculate soil specific weight, SSW.
c     Units: kN/m3.
c
      SSW = SBD*G
c
c     Calculate soil cone index resistance, CI.
c     Units: MPa.
c
      CI = ((SKC*SCR*(EXP(-0.10*MCWW/(1+SCR))))+(SKF*SSW/(1+2*SCR)))*
     &     (EXP(3.1415927/(1+2*SCR)))
c
c     Calculate plough weight, PWT.
c     Units: kN.
c
      PWT = ((7.77 + (147.86*PBS))*9.807)/1000.0
c
c     Calculate total static weight on the tractor, rear and front
c     wheel Sstatic load  PTWT, WDLD & FWLD.
c     Units: kN.
c
      IF (TYPE.EQ.TWOWD) GOTO 9206
      IF (TYPE.EQ.UNE4 ) GOTO 9207
      IF (TYPE.EQ.EQ4W ) GOTO 9208
 9206 IF (TYPE.EQ.TWOWD) PTWT=((2.0*RWLD*9.807/1000.0)/(1-(FLDD/100.0)))
     &                        -PWT
      GOTO 9209
 9207 IF (TYPE.EQ.UNE4 ) PTWT=((2.0*RWLD*9.807/1000.0)/(1-(FLDD/100.0)))
     &                        -PWT
      GOTO 9209
 9208 IF (TYPE.EQ.EQ4W ) PTWT=((4.0*RWLD*9.807)/1000.0)-PWT
 9209 CONTINUE
c
      FWLD = PTWT*(FLDD/100.0)/2.0
      WDLD = (PTWT-(2.0*FWLD))/2.0
c
c     Calculate front and rear wheel section width, FWW & RWW.
c     Units: m.
c
      FWW = FTW*2.54/100.0
      RWW = TRW*2.54/100.0
c
c     Calculate front and rear wheel section height, FTSH & TRSH.
c     Units: m.
c
      FTSH = FWW*0.75
      TRSH = RWW*0.75
c
c     Calculate front and rear tyre deflection, FTDF & TRDF.
c     Units: m.
c
      FTDF = FTSH*0.20
      TRDF = TRSH*0.20
c
c     Calculate front and rear wheel diameter, FTD & TRD
c     Units: m.
c
      FWD = (FRD*2.54/100.0)+2.0*FTSH
```

```
      TRD = (RMD*2.54/100.0)+2.0*TRSH
c
c     Calculate BF, BR for front and rear wheels.
c     Units: none.
c
      BF = (1000.0*CI*FWW*FWD*((FTDF/FTSH)**0.50))/
     &      (1+(FWW/(2.0*FWD)))
      BR = (1000.0*CI*RWW*TRD*((TRDF/TRSH)**0.50))/
     &      (1+(RWW/(2.0*TRD)))
c
c     Calculate tractor rear axle load after transferred takes place, TWR.
c     Units: kN.
c
c     ---------------------------- for two-wheel drive tractor.
      IF (TYPE.EQ.TWOWD) TWR=((1-(0.049*TRD/(2.0*WBAS)))-
     &  ((((1-(0.049*TRD/(2.0*WBAS)))**2.0)-(4.0*2.0*WDLD*
     &  0.287*TRD/(2.0*WBAS*BR)))**0.5))/
     &  (2.0*0.287*TRD/(2.0*WBAS*BR))
c
c     -------------------------- for four-unequal wheel drive tractor.
      IF (TYPE.EQ.UNE4 ) TWR=(((2.0*0.287*PTWT*TRD/(2.0*BF*WBAS))
     &  +1)-(((((2.0*0.287*PTWT*TRD/(2.0*BF*WBAS))+1)**2.0)-
     &  ((4.0*0.287*TRD*(BF+BR)/(2.0*WBAS*BF*BR))*(((PTWT*TRD/
     &  (2.0*WBAS))*((0.287*PTWT/BF)+0.049))+2.0*WDLD)))**0.5))/
     &  (2.0*0.287*TRD*(BF+BR)/(2.0*WBAS*BF*BR))
c     ------------------------- for four-equal wheel drive tractor.
      IF (TYPE.EQ.EQ4W ) TWR=(((2.0*0.287*PTWT*TRD/(2.0*BF*WBAS))
     &  +1)-(((((2.0*0.287*PTWT*TRD/(2.0*BF*WBAS))+1)**2.0)-
     &  ((4.0*0.287*TRD*(BF+BR)/(2.0*WBAS*BF*BR))*(((PTWT*TRD/
     &  (2.0*WBAS))*((0.287*PTWT/BF)+0.049))+2.0*WDLD)))**0.5))/
     &  (2.0*0.287*TRD*(BF+BR)/(2.0*WBAS*BF*BR))
c
c     Calculate dynamic load on the front and rear axle, WF & WR.
c     Units: kN.
c
      WF = PTWT-TWR
      WR = TWR + PWT
c     Calculate front and rear wheel mobility numbers, FMN & WMN.
c     Units: none.
c
      FMN = 2.0*(BF/WF)
      WMN = 2.0*(BR/WR)
c
c     Calculate gear ratio for each speed.
c     Units:none.
c
      RAGR(J8)=((TRD*3.14)*(ENSP*3.6))/(60.0*PS(J8))
c
c     Calculate front and rear wheel slips, FSLIP & RSLIP, and tractor
c     slip, WSLIP.
c     Units: %.
c
      FSLIP = 9.0+(19.0/FMN)
      RSLIP = 9.0+(19.0/WMN)
      IF (TYPE.EQ.TWOWD) WSLIP = RSLIP
      IF (TYPE.EQ.UNE4 ) WSLIP = (FSLIP+RSLIP)/2.0
      IF (TYPE.EQ.EQ4W ) WSLIP = (FSLIP+RSLIP)/2.0
c
c     Calculate front and rear wheel coefficients of rolling resistance,
c     CRRF & CRR.
c     Units: none.
c
      CRRF = 0.049+(0.287/FMN)
      CRR  = 0.049+(0.287/WMN)
```

```
c
c     Calculate front and rear axle rolling resistances, RRF & RRR.
c     Units: kN.
c
      RRF = CRRF* (WF/2.0)
      RRR = CRR * (WR/2.0)
c
c     Calculate front and rear wheel maximum coefficients of traction,
c     CTMAXF & CTMAXF.
c     Units : none.
c
      CTMAXF = 0.796-(0.92/FMN)
      CTMAX  = 0.796-(0.92/WMN)
c
c     Calculate front and rear rate constants, FK & RK.
c     Units: none.
c
      FK = (4.838+0.061*FMN)/CTMAXF
      RK = (4.838+0.061*WMN)/CTMAX
c
c     Calculate coefficients of traction, CTF & CT.
c     Units: none.
c
      CTF = CTMAXF*(1-EXP(-FK*(FSLIP/100.0)))
      CT  = CTMAX *(1-EXP(-RK*(RSLIP/100.0)))
c
c     Calculate front and rear axle maximum tractions, TMAXF & TMAXR and
c     the maximum tractor traction, TMAX.
c     Units: kN.
c
      TMAXF = WF*CTMAXF
      TMAXR = WR*CTMAX
      IF (TYPE.EQ.TWOWD) TMAX = WR*CTMAX
      IF (TYPE.EQ.UNE4 ) TMAX = WF*CTMAXF+WR*CTMAX
      IF (TYPE.EQ.EQ4W ) TMAX = WF*CTMAXF+WR*CTMAX
c
c     Calculate rear axle thrust, (TF1 for 2-WD), or
c     --------- front and rear axle thrusts, (TF1 & TR2 for 4-WD), and
c     --------- tractor thrust, TFR.
c     Units: kN.
c
      TF1 = CTF*WF
      TR2 = CT*WR
      IF (TYPE.EQ.TWOWD) TFR = TR2
      IF (TYPE.EQ.UNE4 ) TFR = TF1+TR2
      IF (TYPE.EQ.EQ4W ) TFR = TF1+TR2
c
c     Calculate net tractor drawbar pull, APULL.
c     units: kN.
c
      IF (TYPE.EQ.TWOWD) APULL = TFR-(2.0*RRF)
      IF (TYPE.EQ.UNE4 ) APULL = TFR
      IF (TYPE.EQ.EQ4W ) APULL = TFR
c
c     Calculate travel reduction, TR.
c     Units: km/h.
c
      TR(J8) = PS(J8)*(WSLIP/100.0)
c
c     Calculate actual travel speed, APS.
c     Units: km/h.
c
      APS(J8) = (PS(J8)-TR(J8))
c
```

```
c      Calculate tractive efficiency from wheel mobility number, TE.
c      Units: %.
c
       IF (TYPE.EQ.TWOWD) TE = 78.0-(55.0/WMN)
       IF (TYPE.EQ.UNE4 ) TE = (2.0*78.0-(55.0/FMN)-(55/WMN))/2.0
       IF (TYPE.EQ.EQ4W ) TE = (2.0*78.0-(55.0/FMN)-(55/WMN))/2.0
c
c      Calculate potential ploughing rate, PPR.
c      Units: ha/h.
c
       PPR(J8) = (PCW*APS(J8)/10.0)*PBS
c
c      Calculate actual ploughing rate, APR.
c      Units: ha/h.
c
       APR(J8) = PPR(J8)*FE/100.0
c
c      Calculate horizontal component of plough draught, PD.
c      Units: kN.
c
       PD(J8)=(((0.05*1000.0*CI)+(9.66*SSW*((APS(J8)/3.6)**2)*(1-COS(
     &       PANGLE))/G))*PCD*PCW)*PBS
c
c      Calculate the torque required at driven wheels, TQ.
c      Units: kNm.
c
       IF (TYPE.EQ.TWOWD) TQ = (TFR+(2.0*RRR))*(TRD/2.0)
       IF (TYPE.EQ.UNE4 ) TQ = (TF1+(2.0*RRF))*(FWD/2.0)+((TR2+(2.0*RRR)
     &                         )/(TRD/2.0))
       IF (TYPE.EQ.EQ4W ) TQ = (TFR+(2.0*(RRF+RRR)))*(TRD/2.0)
c
c      Calculate engine torque required for each speed.
c       Units:Nm.
c
       ENTR(J8) = (TQ*1000.0)/RAGR(J8)
C
c      Calculate total pull required, TPULL.
c      Units: kN.
c
       IF (TYPE.EQ.TWOWD) TPULL = TFR + (2.0*(RRF + RRR))
       IF (TYPE.EQ.UNE4 ) TPULL = TFR + (2.0*(RRF + RRR))
       IF (TYPE.EQ.EQ4W ) TPULL = TFR + (2.0*(RRF + RRR))
c
c      Calculate net drawbar power, equivalent power take-off power
c      tractor power required and maximum engine power, DBKW, PTOKW,
c      PTOKW & MAXTEP.
c      Units: kW.
c
       DBKW(J8) = APULL*(APS(J8)/3.6)
       PTOKW(J8) = ((APULL/0.96)*(APS(J8)/3.6)*100.0)/TE
       TPOWER(J8)= PTOKW(J8)/0.87
       MAXTEP(J8)=(ENTQ*(3.1415*ENSP/30))/1000
c
c      Calculate implement power/ equivalent power-take-off ratio, PTOR.
c      Units: none.
c
       PTOR(J8) = PD(J8)/APULL
c
c      Calculate total dynamic weight on the tractor, TWT.
c      Units: kN.
c
       TWT = WF + WR
c
c      Calculate tractor weight/power ratio, (kg/kW), TRATIO.
```

```
c     Units: none.
c
      IF (TYPE.EQ.TWOWD) TRATIO(J8) = (WR*1000.0/9.807)/MAXTEP(J8)
      IF (TYPE.EQ.UNE4 ) TRATIO(J8) = (TWT*1000.0/9.807)/MAXTEP(J8)
      IF (TYPE.EQ.EQ4W ) TRATIO(J8) = (TWT*1000.0/9.807)/MAXTEP(J8)
c
      PHOURS(J8) = AREA/APR(J8)
      PDAYSR(J8) = PHOURS(J8)/8.0
      PDAYSW = PLCDAY-PLSDAY+1
      EXFPWN = PLCDAY/7.0
      CPDAYN(J8)=(PLSDAY-1) + PDAYSR(J8)
c
      PWDAYS = 0
          J3 = SWNO
          J4 = J3 + 52
      DO 301  JJ1 = J3,J4
              JJJ = JJ1
      IF(JJJ.GT.52) JJJ = JJJ - 52
      PWDAYS = PWDAYS + WDAYS(JJJ)
      IF(PWDAYS.GE.PDAYSR(J8)) GOTO 302
  301 CONTINUE
  302 WEEKNO = JJJ
      IF(PWDAYS.LE.PDAYSW) PDAYS(J8) = 0
      IF(PWDAYS.LE.PDAYSW) PDAYNO(J8)=PLCDAY
      IF(PWDAYS.GT.PDAYSW) PDAYS(J8)=PWDAYS-PDAYSW
      IF(PWDAYS.GT.PDAYSW) PDAYNO(J8)=PLCDAY+PDAYS(J8)
      IF(WEEKNO.GT.CWNO) WEEKS=WEEKNO-CWNO
      FPDAYN(J8) =PDAYNO(J8)
      RPDS(J8)=PDAYSR(J8)
      PWWN(J8)=WEEKNO
      IF (TE.LT.0.65) GOTO 118
      IF ((0.75*APULL).GT.PD(J8)) GOTO 118
      IF (APULL.LT.PD(J8)) GOTO 118
      IF (ENTR(J8).GE.ENTQ) GOTO 118
      ID = ID + 1
      FWW1(ID) = FTW
      RWW2(ID) = TRW
      FRDM1(ID) = FRD
      RRDM2(ID) = RMD
      FWP1(ID) = FINFP
      RWP2(ID) = TINFP
      PERHR(ID) = APR(J8)
      ENGINE(ID) = MAXTEP(J8)
      BODIES(ID) = PBS
      DRBKW(ID) = DBKW(J8)
      TSLIP(ID) = WSLIP
      SINE(ID) = IDDD
      PTORA(ID) = PTOR(J8)
      PTOP(ID) = PTOKW(J8)
      RPDS(ID) = PDAYSR(J8)
c
      IF (TYPE.EQ.TWOWD)    CTF = 0.0
      IF (TYPE.EQ.TWOWD)     FK = 0.0
      IF (TYPE.EQ.TWOWD) CTMAXF = 0.0
      IF (TYPE.EQ.TWOWD)   CRRF = 0.0
      IF (TYPE.EQ.TWOWD)    FMN = 0.0
      IF (TYPE.EQ.TWOWD)    TF1 = 0.0
      IF (TYPE.EQ.TWOWD)  TMAXF = 0.0
c
      WRITE(LURT,81) AOR(I),FWW1(ID),FRDM1(ID),RWW2(ID),RRDM2(ID),
     &                FWP1(ID),RWP2(ID),FLDD,FWLD,WDLD,TTUSEH,PBS,PANGLE,
     &                ENTQ,ENSP,ENGINE(ID)
   81 FORMAT(1H ,I2,X,F4.1,'-',F4.1,X,F4.1,'-',F4.1,2(X,F5.1),
     &           3(X,F5.2),X,F6.1,2X,I2,X,F5.2,X,F6.1,2(X,I6))
```

```
c
      WRITE(5,1155) J8,PCD,PCW,SSW,CI,FWLD,WDLD,PTWT,PWT,TWT,
     &                WF,WR,FWW,RWW,FTSH,TRSH,FTDF,TRDF,FWD,TRD
 1155 FORMAT(1H , I4,4(F8.3),15(F10.3))
      WRITE(9,1151)  FMN,WMN,FSLIP,RSLIP,CRRF,CRR,RRF,RRR,CTMAXF,
     &               CTMAX,CTF,CT,FK,RK,TMAXF,TMAXR,TMAX,TF1,TR2,
     &              TFR,TE,RAGR(J8),PD(J8),TR(J8),APS(J8),APULL,
     &               TPULL,ENTR(J8),TRATIO(J8),TPOWER(J8)
 1151 FORMAT(1H , 30(F8.3))
c
      WRITE(7,701) WEEKNO,FPDAYN(J8),PDAYS(J8),CPDAYN(J8)
  701 FORMAT(1H ,4(I6))
  118 CONTINUE
   77 CONTINUE
   66 CONTINUE
   44 CONTINUE
   33 CONTINUE
   22 CONTINUE
   88 CONTINUE
   11 CONTINUE
c
      CLOSE(UNIT=5)
      CLOSE(UNIT=9)
      CLOSE(UNIT=7)
c
      WRITE(LURT,91)
   91 FORMAT(1H0,  92('-'))
c
      END
```

INTEGER

LINEAR

PROGRAMMING

MODEL

APPENDIX C1

Generator program

GENERATOR PROGRAM
(LP80P1)

```
%begin
! FAWCETT AGR001 LP PROGRAM 2.7.70 CD
   %integer I,J,M,N,K,KP,Z,L,FAIL,TRAN,SIGN,ROWS,COLS,TS,KILL,L1,L2,L3,LIST,
      NP,NK,LONG
   %integer EVENT,SUBEVENT
   %long %real T,MINN,MINP,TE,X,RALPH,INTSOL,PTMAX
   %string (255) TEXT
   %const %integer %array EVENTLABEL(10:81)=125,101,102,117,122,123,124,127,
   100(3),104,100(9),118,100(9),114,100(9),103,105,106,107,121,128,
   100(4),130,132,100(8),126,100(9),131
   %switch SW(100:132)
   %on %event 1,2,3,4,5,6,7,8,10 %start
      EVENT = EVENTINF>>8
      SUBEVENT = EVENTINF&X'FF'
      ->SW(125) %if EVENT=10
      ->SW(EVENTLABEL(10*EVENT+SUBEVENT))
   %finish
   SELECT INPUT(1)
   SELECT OUTPUT(2)
   LIST = 5000
   NP = 0
   NK = 0
   LONG = 0
!
!
!
   %routine PRESTRING
      %integer S
A1:   S = NEXTSYMBOL
      %return %if S=''''
      ->A2 %unless S=' ' %or S=NL
      SKIPSYMBOL
      ->A1
A2:   NEWLINE
      PRINTSTRING(" UNEXPECTED DATA IN STRING STREAM: ")
A3:   READSYMBOL(S)
      PRINTSYMBOL(S)
      ->A3 %unless NEXTSYMBOL=''''
   %end
!
!
!
   KILL = 2
START: PRESTRING
   READ STRING(TEXT)
   PRINT STRING(TEXT)
   NEWLINES(3)
RESTART 1: KILL = 1
   FAIL = 0
   TRAN = 0
   SIGN = 0
A7: READ(T)
   ->A8 %unless T=1@5
   PRINTSTRING(" JOB TERMINATED NORMALLY ")
   %stop
A8: PRINTSTRING("
```

```
DATA NO.=")
   PRINT(T,1,3)
   NEWLINE
   PRESTRING
   READ STRING(TEXT)
   PRINT STRING(TEXT)
   NEWLINE
   READ(L1)
   READ(L2)
   READ(L3)
   READ(T)
   READ(M)
   READ(N)
   READ(KP)
A1: READ SYMBOL(TS)
   ->A2 %if TS=NL
   TRAN = 1 %if TS='T'
   SIGN = 1 %if TS='S'
   ->A1
A2: I = 0
   KILL = 0
!
!
!
RESTART 2: %begin
      %long %real %array AP(1:M+1,1:N+1),C(1:N),D(1:M),LT,PT(0:LIST),DS(1:LIS'
      %integer %array A(1:M),B(1:N),LS(L1:L2,0:LIST),PK(0:LIST),DI(1:LIST)
      %integer S
!
!
!
      %routine TRANSIGN 1(%long %real X, %long %real %array %name DATA,
         %integer ROW,COL)
         DATA(ROW,COL) = X
      %end
!
!
!
      %routine TRANSIGN 2(%long %real X, %long %real %array %name DATA,
         %integer ROW,COL)
         DATA(ROW,COL) = -X
      %end
!
!
!
      %routine TRANSIGN 3(%long %real X, %long %real %array %name DATA,
         %integer ROW,COL)
         DATA(COL,ROW) = X
      %end
!
!
!
      %routine TRANSIGN4(%long %real X, %long %real %array %name DATA,
         %integer ROW,COL)
         DATA(COL,ROW) = -X
      %end
!
!
!
      %routine INPUT(%routine TRANSIGN(%long %real X,
         %long %real %array %name DATA, %integer ROW,COL))
         %cycle I = I,1,ROWS
            J = 0
A1:         J = J+1
```

```
A2:          S = NEXTSYMBOL
             ->A3 %unless S=' ' %or S=NL %or S='N'
             SKIPSYMBOL
             ->A2
A3:          ->A4 %if NEXTSYMBOL='Z'
             READ(X)
             TRANSIGN(X,AP,I,J)
             ->A10
A4:          SKIPSYMBOL
             READ(Z)
             %cycle J = J,1,J+Z-1
                TRANSIGN(0,AP,I,J)
             %repeat
A10:         S = NEXTSYMBOL
             ->A11 %unless S=' ' %or S=NL
             SKIPSYMBOL
             ->A10
A11:         ->A12 %if J=COLS
             ->A1 %unless NEXTSYMBOL='N'
             NEWLINE
             PRINTSTRING(" FAULT - TOO FEW DATA VALUES IN INPUT ROW ")
             WRITE(I,1)
             ->A18
A12:         ->A20 %if NEXTSYMBOL='N'
!CORRECT NUMBER ON LINE(I)
             NEWLINE
             PRINTSTRING(" FAULT - TOO MANY DATA VALUES IN INPUT ROW ")
             WRITE(I,1)
             SPACES(6)
A13:         READSYMBOL(J)
             PRINTSYMBOL(J)
             ->A13 %unless J='N'
A18:         FAIL = FAIL+1
             ->A20
A20:      %repeat
A21:      SKIPSYMBOL
          S = NEXTSYMBOL
          ->A21 %if S=' ' %or S=NL
          ->A30 %if S='E'
          NEWLINE
          PRINTSTRING(" FAULT - TOO MANY ROWS IN MATRIX ")
          FAIL = FAIL+1
A30:      SKIPSYMBOL
          ->A30 %unless NEXTSYMBOL=NL
          KILL = 1
       %end
!
!
!
       I = I+1
       ->A2 %if TRAN=1
       ROWS = M+1
       COLS = N+1
       ->A1 %if SIGN=1
       INPUT(TRANSIGN 1)
       ->A4
A1:    INPUT(TRANSIGN 2)
       ->A4
A2:    ROWS = N+1
       COLS = M+1
       ->A3 %if SIGN=1
       INPUT(TRANSIGN 3)
       ->A4
A3:    INPUT(TRANSIGN4)
```

```
A4:    ->A5 %unless FAIL>0
       PRINTSTRING(" ANALYSIS NOT ATTEMPTED BECAUSE OF INPUT FAULTS ")
       ->A500
A5:    NEWLINE
       %cycle I = 1,1,M+1
          %cycle J = 1,1,N+1
             PRINT(AP(I,J),6,2)
             NEWLINE %if J=10*(J//10)
          %repeat
          NEWLINE
       %repeat
       %cycle I = 1,1,N
          C(I) = AP(M+1,I)
       %repeat
       %cycle I = 1,1,M
          D(I) = AP(I,N+1)
       %repeat
       %cycle I = 0,1,LIST
          LT(I) = 0
          PK(I) = 0
       %repeat
       %cycle I = 1,1,LIST
          DS(I) = -1@23
          PT(I) = -1@23
          DI(I) = 0
       %repeat
       RALPH = -1@23
       PTMAX = -1@23
       INTSOL = -1@23
       %cycle J = 0,1,LIST
          %cycle I = L1,1,L2
             LS(I,J) = -10
          %repeat
       %repeat
!
!
!
       SELECT OUTPUT(3)

       KP = 1
       WRITE(L1,4)
       WRITE(L2,4)
       WRITE(L3,4)
       PRINT FL(T,1)
       WRITE(M,4)
       WRITE(N,4)
       WRITE(KP,4)
       WRITE(LIST,4)
       WRITE(NP,4)
       WRITE(NK,4)
       WRITE(LONG,4)
       %cycle I = 0,1,LIST
          PRINT(LT(I),6,2)
          WRITE(PK(I),6)
       %repeat
       %cycle I = 1,1,LIST
          PRINT(DS(I),6,2)
          PRINT(PT(I),6,2)
          WRITE(DI(I),6)
       %repeat
       NEWLINE
       PRINT(RALPH,6,2)
       PRINT(PTMAX,6,2)
       PRINT(INTSOL,6,2)
```

```
      %cycle J = 0,1,LIST
         %cycle I = L1,1,L2
            WRITE(LS(I,J),6)
         %repeat
      %repeat
      NEWLINE
      %cycle I = 1,1,M+1
         %cycle J = 1,1,N+1
            PRINT FL(AP(I,J),4)
         %repeat
         NEWLINE
      %repeat
      %cycle I = 1,1,M
         PRINT FL(D(I),4)
      %repeat
A500: %end
!
!
!
   NEWPAGE
   ->RESTART 1
!
!
!
   %routine FT(%integer N)
      PRINTSTRING("
********** FAULT")
      PRINT(N,4,0)
      PRINTSTRING(" TRAPPED ")
      %monitor
      NEWLINE
      FAIL = FAIL+1
      %monitor %and %stop %if FAIL>10
   %end
!
!
!
   %routine SAF
      %integer S
      PRINTSTRING("ROW")
      WRITE(I,3)
      PRINTSTRING("   COLUMN")
      WRITE(J,3)
      PRINTSTRING(" SYMBOLS AFTER FAULT: ")
A1:   READ SYMBOL(S)
      PRINT SYMBOL(S)
      ->A1 %unless S=NL
      NEWLINES(2)
   %end
!
!
!
SW(101): FT(1)
   ->L200
SW(102): FT(2)
   ->L200
SW(103): FT(3)
   ->L200
SW(104): FT(4)
   ->L200
SW(105): FT(5)
   ->L200
SW(106): FT(6)
   ->L200
```

```
SW(107): FT(7)
   ->L200
SW(110): FT(10)
   ->L200
SW(111): FT(11)
   ->L200
SW(114): FT(14)
   SAF
   ->L201
SW(116): FT(16)
   SAF
   ->L201
SW(117): FT(17)
   ->L200
SW(118): FT(18)
   SAF
   ->L201
SW(121): FT(21)
   ->L200
SW(122): FT(22)
   ->L200
SW(123): FT(23)
   ->L200
SW(124): FT(24)
   ->L200
SW(125): FT(25)
   ->L200
SW(126): FT(26)
   ->L200
SW(127): FT(27)
   ->L200
SW(128): FT(28)
   ->L200
SW(130): FT(30)
   ->L200
SW(131): FT(31)
   ->L200
SW(132): FT(32)
   ->L200
L200: PRINTSTRING(" ANALYSIS ABANDONED")
L201: PRINTSTRING("INPUT FAULT - WILL NOW ATTEMPT TO RECOVER ")
   NEWLINES(5)
   ->RESTART 1 %if KILL=1
   ->RESTART 2 %if KILL=0
   PRINTSTRING("
JOB ABANDONED ")
SW(100): %end %of %program
```

APPENDIX C2

Integerisation Program

INTEGER LINEAR PROGRAM
(INTEGER)

```
!
%begin
! FAWCETT AGR001 LP PROGRAM 2.7.70 CD
   %integer I,J,M,N,K,KP,Z,L,L1,IS,NF,L2,L3,LIST,NP,NK,LONG,CP,DP,TYPE,MP1,NP1
   %long %real T,MINN,MINP,TE,X,V,RALPH,TEST,INTSOL,PTMAX,TIME,TX
   %string (255) TEXT
   %external %routine %spec EMAS3CPUTIME(%long %real %name TIME)
   EMAS3CPUTIME(TIME)
   SELECT INPUT(1)
   SELECT OUTPUT(2)
   TX = TIME
   DP = 0
   CP = 0
   READ(L1)
   READ(L2)
   READ(L3)
   READ(T)
   READ(M)
   READ(N)
   READ(KP)
   READ(LIST)
   READ(NP)
   READ(NK)
   READ(LONG)
   TYPE = 1
   %begin
      %long %real %array AP,BP(1:M+1,1:N+1),C(1:N),D(1:M),LT,PT(0:LIST),
         DS(1:LIST)
      %integer %array A(1:M),B(1:N),LS(L1:L2,0:LIST),PK(0:LIST),DI(1:LIST)
      %cycle I = 0,1,LIST
         READ(LT(I))
         READ(PK(I))
      %repeat
      %cycle I = 1,1,LIST
         READ(DS(I))
         READ(PT(I))
         READ(DI(I))
      %repeat
      READ(RALPH)
      READ(PTMAX)
      READ(INTSOL)
      %cycle J = 0,1,LIST
         %cycle I = L1,1,L2
            READ(LS(I,J))
         %repeat
      %repeat
      %cycle I = 1,1,M+1
         %cycle J = 1,1,N+1
            READ(BP(I,J))
                                               !READ(AP(I,J))
                                               !BP(I,J) = AP(I,J)
         %repeat
      %repeat
!
!
!
      %cycle I = 1,1,N
         C(I) = BP(M+1,I)
```

INTEGER LINEAR PROGRAM
(INTEGER)

```
!
%begin
! FAWCETT AGR001 LP PROGRAM 2.7.70 CD
   %integer I,J,M,N,K,KP,Z,L,L1,IS,NF,L2,L3,LIST,NP,NK,LONG,CP,DP,TYPE,MP1,NP1
   %long %real T,MINN,MINP,TE,X,V,RALPH,TEST,INTSOL,PTMAX,TIME,TX
   %string (255) TEXT
   %external %routine %spec EMAS3CPUTIME(%long %real %name TIME)
   EMAS3CPUTIME(TIME)
   SELECT INPUT(1)
   SELECT OUTPUT(2)
   TX = TIME
   DP = 0
   CP = 0
   READ(L1)
   READ(L2)
   READ(L3)
   READ(T)
   READ(M)
   READ(N)
   READ(KP)
   READ(LIST)
   READ(NP)
   READ(NK)
   READ(LONG)
   TYPE = 1
   %begin
      %long %real %array AP,BP(1:M+1,1:N+1),C(1:N),D(1:M),LT,PT(0:LIST),
         DS(1:LIST)
      %integer %array A(1:M),B(1:N),LS(L1:L2,0:LIST),PK(0:LIST),DI(1:LIST)
      %cycle I = 0,1,LIST
         READ(LT(I))
         READ(PK(I))
      %repeat
      %cycle I = 1,1,LIST
         READ(DS(I))
         READ(PT(I))
         READ(DI(I))
      %repeat
      READ(RALPH)
      READ(PTMAX)
      READ(INTSOL)
      %cycle J = 0,1,LIST
         %cycle I = L1,1,L2
            READ(LS(I,J))
         %repeat
      %repeat
      %cycle I = 1,1,M+1
         %cycle J = 1,1,N+1
            READ(BP(I,J))
                                          !READ(AP(I,J))
                                          !BP(I,J) = AP(I,J)
         %repeat
      %repeat
!
!
!
      %cycle I = 1,1,N
         C(I) = BP(M+1,I)
```

```
%repeat
%cycle I = 1,1,M
   READ(D(I))
%repeat
!
!
!
%routine EXTENDEDCOMPOSITE(%long %real %array %name AP,
   %integer %array %name BV,N BV, %integer M,N, %long %real T)
   %integer H,I,J,K,R,IMIN
   %long %real MIN,DUMP,TOTAL
   %long %real %array F(1:M)
!
!
!
   %routine PIVOTP(%integer %name R,H, %integer M,N)
      DUMP = AP(R,H)
      I = NBV(H)
      NBV(H) = BV(R)
      BV(R) = I
      %cycle I = 1,1,M
         %if I=R %then ->P18
         %cycle J = 1,1,N
            %if J=H %then ->P17
            AP(I,J) = AP(I,J)-(AP(R,J)*AP(I,H))/DUMP
P17:     %repeat
P18:  %repeat
      %cycle I = 1,1,M
         AP(I,H) = -AP(I,H)/DUMP
      %repeat
      %cycle I = 1,1,N
         AP(R,I) = AP(R,I)/DUMP
      %repeat
      AP(R,H) = -AP(R,H)
      Z = Z+1
   %end
!
!
!
   %routine MINIMISEP(%long %real %array %name AP,PP, %integer M,N)
      %integer I,J,R,H,A
      %long %real DUMP,TRIAL
M4:                                       ! SEARCHAP(M,J)*FORLARGESTELEMENT
      TRIAL = AP(M,1)
      NF = 0
      A = 1
      %cycle I = 2,1,N-1
         %if AP(M,I)<=TRIAL %then ->M19
         TRIAL = AP(M,I)
         A = I
M19:  %repeat
      H = A
      %if AP(M,H)<=T %then %return
M6:   %cycle I = 1,1,M-1
         %if AP(I,H)<T %then ->M9
         PP(I) = AP(I,N)/AP(I,H)
         ->M16
M9:      PP(I) = 1@6
M16:  %repeat
      DUMP = 0
      %cycle I = 1,1,M-1
         DUMP = DUMP+PP(I)
      %repeat
      %unless DUMP=(M-1)*(1@6) %then ->M2
```

```
            PRINTSTRING("
FAULT IN DATA
NO FINITE SOLUTION")
            NF = 1
            ->M20
!ORCHARD-HAYS SELECTION FOR TIED PIVOTAL ROWS
M2:         MIN = PP(1)
            R = 1
            %cycle I = 2,1,M-1
               ->M1 %if PP(I)>MIN
               ->M5 %if PP(I)<MIN
               ->M1 %if AP(I,H)<=AP(R,H)
M5:            MIN = PP(I)
               R = I
M1:         %repeat
            PIVOTP(R,H,M,N)
            ->M4
M20:     %end
!
!
!
         %cycle I = 1,1,N
            NBV(I) = I
         %repeat
         %cycle I = 1,1,M
            BV(I) = I+1000
         %repeat
! FIND FEASIBLE SOLUTION
         Z = 0
A5:      %cycle I = 1,1,M
           %if AP(I,N+1)<-T %then ->A1
         %repeat
         L = Z
         PRINTSTRING("
BASIC FEASIBLE SOLUTION OBTAINED
")
         ->A3
A1:      MIN = 999999
         %cycle J = 1,1,N
            TOTAL = 0
            %cycle I = 1,1,M
               %if AP(I,N+1)>-T %then ->A14
               TOTAL = TOTAL+AP(I,J)
A14:        %repeat
            %if TOTAL>=MIN %then ->A15
            MIN = TOTAL
            H = J
A15:     %repeat
         %if MIN<0 %then ->A2
         PRINTSTRING("
FAULT IN DATA
NO BASIC FEASIBLE SOLUTION")
         NF = 1
         ->A200
A2:                                                ! HGIVESPIVOTALCOLUMNNO
         %cycle I = 1,1,M
            %if MOD(AP(I,H))<T %then ->A13
            F(I) = AP(I,N+1)/AP(I,H)
            TOTAL = 0
            %cycle J = 1,1,M
               DUMP = AP(J,N+1)-AP(J,H)*F(I)
               %if DUMP<0 %then TOTAL = TOTAL+DUMP
            %repeat
            F(I) = -TOTAL
```

```
              ->A12
A13:          F(I) = 999999999
A12:       %repeat
           MIN = F(1)
           IMIN = 1
           %cycle I = 2,1,M
              %if F(I)>MIN %then ->A23
              MIN = F(I)
              IMIN = I
A23:       %repeat
           R = IMIN
           PIVOTP(R,H,M+1,N+1)
           ->A5
A3:        NEWLINE
           MINIMISEP(AP,F,M+1,N+1)
           ->A200 %if NF=1
           PRINTSTRING("
LP SOLUTION OBTAINED.")
A200: %end
!
!
!
       MP1 = M+1
       NP1 = N+1
C10:   %if MOD(LT(NP))>T %then ->C100
       %if NP>LIST %then ->C100
       %if NP>LONG %then ->C100
       EMAS3CPUTIME(TIME)
       %if TIME>3300 %then ->C300
       %cycle I = 1,1,MP1
          %cycle J = 1,1,NP1
             AP(I,J) = BP(I,J)
          %repeat
       %repeat
       NEWLINE
       PRINTSTRING("ITERATION NO ")
       SPACES(5)
       WRITE(NK,4)
       NEWLINE
       PRINTSTRING("TIME = ")
       PRINT(TIME,6,6)
       NEWLINE
       PRINT(INTSOL,6,2)
       SPACES(2)
       PRINT(RALPH,6,2)
       NEWLINE
       PRINTSTRING("NEXT FROM THE LIST")
       WRITE(NP,4)
       NEWLINE
       PRINTSTRING("INTEGER RESTRAINTS")
       %cycle I = L1,1,L2
          K = I+L3-L1
          AP(MP1,K) = LS(I,NP)
          %if LS(I,NP)>T %then TYPE = 0
NEWLINE
PRINTSTRING("TYPE=")
WRITE(TYPE,1)
          %unless TYPE=0 %then ->C11
          AP(MP1,K) = -AP(M+1,K)
          %cycle J = 1,1,MP1
             %if AP(J,K)=0 %then %continue
             AP(J,K) = -AP(J,K)
          %repeat
          TYPE = 1
```

```
C11:         SPACES(2)
          WRITE(K,4)
          SPACES(4)
          PRINT(AP(MP1,K),4,2)
       %repeat
!
!
!
!
       EXTENDEDCOMPOSITE(AP,A,B,M,N,T)
       LT(NP) = (AP(MP1,NP1))
       %if NF=1 %then LT(NP) = -1@23
NEWLINE
       PRINTSTRING("OBJECTIVE FN  NF")
       NEWLINE
       PRINT(LT(NP),6,2)
       SPACES(2)
       WRITE(NF,3)
NEWLINE
       %if NF=1 %then ->C30
       NEWLINE
       PRINTSTRING("INTEGER VARIABLES")
       NEWLINE
       IS = 0
       %cycle I = 1,1,N
          ->A50 %if B(I)<=N
          ->A50 %unless B(I)-1000>=L1 %and B(I)-1000<L2+1
          PRINT(B(I),4,0)
          SPACES(3)
          PRINT((-AP(MP1,I)),3,2)
NEWLINE
          ->A50 %unless FRAC PT(-AP(MP1,I))>T
          ->A50 %unless FRAC PT(-AP(MP1,I))<1-T
          %if IS>0 %then ->A45
          IS = B(I)-1000
          DP = INT PT(MOD(AP(MP1,I)))+1
          CP = DP-1
A45:      SPACES(2)
          PRINTSTRING("FRAC PT=")
          PRINT FL(FRAC PT(-AP(MP1,I)),8)
     SPACES(2)
NEWLINE
A50:        %repeat
       PRINTSTRING("IS =")
       WRITE(IS,6)
       ->C50 %if IS=0
       ->C30 %if LT(NP)<INTSOL
       LONG = LONG+2
       %if LONG>LIST %then ->C200
       %cycle I = L1,1,L2
          LS(I,LONG) = LS(I,NP)
          LS(I,LONG-1) = LS(I,NP)
       %repeat
       write(long-1,4)
       spaces(2)
       write(-cp,2)
       spaces(2)
       write(long,4)
       spaces(2)
       write(dp,2)
       LS(IS,LONG-1) = -CP
       LS(IS,LONG) = DP
       PK(LONG) = 1
       PK(LONG-1) = 1
```

```
      PT(LONG-1) = LT(NP)
      PT(LONG) = LT(NP)
 C50: ->C30 %unless IS=0
      NEWLINE
      SELECT OUTPUT(3)
      KP = 1
      PRINT FL(T,1)
      WRITE(N,4)
      WRITE(M,4)
      WRITE(KP,4)
      NEWLINE
      %cycle I = 1,1,N
         WRITE(B(I),4)
      %repeat
      NEWLINE
      %cycle I = 1,1,M
         WRITE(A(I),4)
      %repeat
      NEWLINE
      %cycle I = 1,1,NP1
         %cycle J = 1,1,MP1
            PRINT FL(AP(J,I),8)
            %if MOD(AP(J,I))<1@-76 %then AP(J,I) = 0
         %repeat
         NEWLINE
      %repeat
      SELECT OUTPUT(2)
      DS(NP) = LT(NP)
      DI(NP) = NK
      ->C55 %if DS(NP)<INTSOL
      INTSOL = DS(NP)
      PRINTSTRING("INTSOL = ")
      PRINT(INTSOL,6,2)
      NEWLINE
 C55: PTMAX = -1@23
      %cycle I = 1,1,LONG
         %if PK(I)=0 %then %continue
         %if PT(I)<PTMAX %then %continue
         PTMAX = PT(I)
      %repeat
      %if INTSOL<PTMAX %then ->C30
      %cycle J = 1,1,LONG
         %if INTSOL>DS(J) %then %continue
         NP = J
      %repeat
      PRINTSTRING("ITERATION = ")
      WRITE(DI(NP),4)
      NEWLINE
      PRINTSTRING("OBJECTIVE FUNCTION = ")
      PRINT(DS(NP),6,2)
      NEWLINE
      PRINTSTRING("OPTIMUM SOLUTION OBTAINED")
      NEWLINE
      %stop
 C30: NK = NK+1
      NP = 0
      ralph = -1@23
      %cycle I = 1,1,LONG
         %if PK(I)=0 %then %continue
         %if PT(I)<RALPH %then %continue
         RALPH = PT(I)
         NP = I
      %repeat
      %if RALPH<INTSOL %then ->C99
```

```
      PK(NP) = 0
      ->C10
C99:  PRINTSTRING("INTEGER SOLUTION BEST POSSIBLE")
newline
      ->C110
C100: PRINTSTRING("JOB TERMINATED LIST COMPLETE")
      NEWLINE
C110: TEST = -1@23
      %cycle I = 1,1,LONG
         %if DI(I)=0 %then %continue
         %if DS(I)<TEST %then %continue
         NK = I
      %repeat
      PRINTSTRING("ITERATION = ")
      WRITE(DI(NK),4)
      NEWLINE
      PRINTSTRING("OBJECTIVE FUNCTION = ")
      PRINT(DS(NK),6,2)
      NEWLINE
      %stop
C200: PRINTSTRING("JOB TERMINATED LIST EXCEEDED")
      NEWLINE
      %stop
C300: PRINTSTRING("TIME EXCEEDED")
      SELECT OUTPUT(4)
      KP = 1
      WRITE(L1,4)
      WRITE(L2,4)
      WRITE(L3,4)
      PRINT FL(T,1)
      WRITE(M,4)
      WRITE(N,4)
      WRITE(KP,4)
      WRITE(LIST,4)
      WRITE(NP,4)
      WRITE(NK,4)
      WRITE(LONG,4)
      %cycle I = 0,1,LIST
         PRINT(LT(I),6,2)
         WRITE(PK(I),6)
      %repeat
      %cycle I = 1,1,LIST
         PRINT(DS(I),6,2)
         PRINT(PT(I),6,2)
         WRITE(DI(I),6)
      %repeat
      NEWLINE
      PRINT(RALPH,6,2)
      PRINT(PTMAX,6,2)
      PRINT(INTSOL,6,2)
      %cycle J = 0,1,LIST
         %cycle I = L1,1,L2
            WRITE(LS(I,J),6)
         %repeat
      %repeat
      NEWLINE
      %cycle I = 1,1,M+1
         %cycle J = 1,1,N+1
            PRINT FL(BP(I,J),4)
         %repeat
      %repeat
      %cycle I = 1,1,M
         PRINT FL(D(I),4)
      %repeat
         %end
      %end %of %program
```

APPENDIX C3

Interpreter Program

INTERPRETER PROGRAM
(LP87PR)

```
%begin
! FAWCETT AGR001 LP PROGRAM 2.7.70 CD
   %integer I,J,M,N,K,KP,Z
   %long %real T,MINN,MINP,TE
   %string (255) TEXT
   Z = 0
   SELECT INPUT(1)
   SELECT OUTPUT(2)
   READ(T)
   %if T>=1@5 %then %stop
   READ(M)
   READ(N)
   READ(KP)
   %begin
      %long %real %array AP(1:M+1,1:N+1),C(1:N)
      %integer %array A(1:M),B(1:N)
      %string (7) %array VA(1:N)
      %string (7) %array RE(1:M)
      %onevent 9  %start
         %stop
      %finish
      NEWLINE
      PRINTSTRING("BV.NOS.(ROWS)
")
      NEWLINE
      PRINTSTRING("NBV.NOS.(COLS)
")
      NEWLINE
C10:  ->C15 %if Z=0
      READ(T)
      %if T>=1@5 %then %stop
      READ(M)
      READ(N)
      READ(KP)
      PRINTSTRING("SOLUTION")
      WRITE((Z+1),2)
      NEWLINE
C15:  %cycle I = 1,1,M
         READ(A(I))
         %if A(I)>1000 %then A(I) = A(I)-1000 %else A(I) = A(I)+1000
      %repeat
      %cycle I = 1,1,N
         READ(B(I))
         %if B(I)>1000 %then B(I) = B(I)-1000 %else B(I) = B(I)+1000
      %repeat
      %cycle J = 1,1,M+1
         %cycle I = 1,1,N+1
            READ(AP(J,I))
            %if MOD(AP(J,I))<1@-76 %then AP(J,I) = 0
            AP(J,I) = -AP(J,I)
         %repeat
      %repeat
!
!
!
!
!
      %cycle I = 1,1,N
        C(I) = AP(M+1,I)
```

```
      %repeat
      ->C20 %if Z>0
!
!
!
!
      SELECT INPUT(3)
      READSTRING(TEXT)
      %cycle I = 1,1,N
         READSTRING(VA(I))
      %repeat
      READSTRING(TEXT)
      %cycle I = 1,1,M
         READSTRING(RE(I))
      %repeat
      SELECT INPUT(1)
C20:  Z = Z+1
      NEWLINE
      PRINTSTRING("OBJECTIVE FUNCTION VALUE=")
      PRINT(AP(M+1,N+1),6,2)
      NEWLINE
      PRINTSTRING("
BASIC VARIABLES
")
      SPACES(2)
      PRINTSTRING("  BV.    VALUE    CHANGE   P.CENT  NBV.IN       ")
      PRINTSTRING("PERMISS. RANGE    CHANGE   P.CENT  NBV.IN")
      SPACES(14)
      PRINTSTRING("BV.     VALUE
")
      %cycle I = 1,1,M
         SPACES(97) %if A(I)>1000
         PRINTSTRING(VA(A(I))) %unless A(I)>1000
         PRINTSTRING(RE(A(I)-1000)) %if A(I)>1000
         SPACES(2)
         PRINT(AP(I,N+1),4,2)
         SPACES(2)
         ->A35 %if A(I)>1000
         MINP = 99999999
         MINN = -MINP
         %cycle J = 1,1,N
            ->A31 %if T>AP(I,J)>-T
            TE = AP(M+1,J)/AP(I,J)
            MINN = TE %if MINN<TE<-T
            K = B(J) %if MINN=TE
            MINP = TE %if MINP>TE>T
            KP = B(J) %if MINP=TE
A31:     %repeat
         ->A32 %if MINN#-99999999
         PRINTSTRING("   INF.")
         SPACES(23)
         PRINTSTRING("INF.  ")
         ->A33
A32:     PRINT(MINN,3,2)
         SPACES(2)
         ->A8 %unless T>C(A(I))>-T %or MOD(MINN/C(A(I)))>=100
         PRINTSTRING("  >=1@4")
         ->A9
A8:      PRINT(MOD(MINN*100/C(A(I))),4,1)
A9:      SPACES(2)
         PRINT(K,4,0)
         SPACES(3)
         PRINT((C(A(I))+MINN),4,2)
         SPACES(2)
```

```
A33:     ->A34 %if MINP#99999999
         PRINTSTRING("    INF.       INF.")
         ->A35
A34:     PRINT((C(A(I))+MINP),4,2)
         SPACES(3)
         PRINT(MINP,3,2)
         SPACES(2)
         ->A10 %unless T>C(A(I))>-T %or MOD(MINP/C(A(I)))>=100
         PRINTSTRING("  >=1@4")
         ->A11
A10:     PRINT(MOD(MINP*100/C(A(I))),4,1)
A11:     SPACES(2)
         PRINT(KP,4,0)
A35:     NEWLINE
      %repeat
      NEWLINE
      PRINTSTRING("

NON-BASIC VARIABLES
")
      SPACES(3)
      PRINTSTRING(" NBV      M.V.P   P.CENT     REQ.PR   UNITS IN    BV.OUT")
      SPACES(13)
      PRINTSTRING("NBV.      M.V.P   UN.INCR    BV.OUT  UN.DECR    BV.OUT
")
      %cycle I = 1,1,N
         MINN = 99999999
         MINP = -MINN
         ->A40 %if B(I)<=N
         %cycle J = 1,1,M
            ->A41 %if T>AP(J,I)>-T
            TE = AP(J,N+1)/AP(J,I)
            MINN = TE %if MINN>TE>T
            K = A(J) %if MINN=TE
            MINP = TE %if MINP<TE<-T
            KP = A(J) %if MINP=TE
A41:     %repeat
         SPACES(65)
         B(I) = B(I)-1000
         PRINTSTRING(RE(B(I)))
         SPACES(3)
         PRINT((-AP(M+1,I)),3,2)
         SPACES(2)
         ->A42 %if MINP#-99999999
         PRINTSTRING("  INF.")
         SPACES(12)
         ->A43
A42:     PRINT((-MINP),4,2)
         SPACES(3)
         PRINT(KP,4,0)
         SPACES(2)
A43:     ->A44 %if MINN#99999999
         PRINTSTRING("  INF.")
         ->A45
A44:     PRINT((-MINN),4,2)
         SPACES(3)
         PRINT(K,4,0)
         ->A45
A40:     %cycle J = 1,1,M
            ->A46 %if AP(J,I)<T
            TE = AP(J,N+1)/AP(J,I)
            MINN = TE %if MINN>TE
            K = A(J) %if MINN=TE
A46:     %repeat
```

```
          PRINTSTRING(VA(B(I)))
          SPACES(3)
          PRINT((-AP(M+1,I)),3,2)
          SPACES(2)
          ->A12 %unless T>C(B(I))>-T %or MOD(AP(M+1,I)/C(B(I)))>=100
          PRINTSTRING("  ")
          PRINTSTRING("4")
          ->A13
A12:      PRINT(MOD(AP(M+1,I)*100/C(B(I))),4,1)
A13:      SPACES(2)
          PRINT((C(B(I))-AP(M+1,I)),4,2)
          SPACES(2)
          ->A47 %if MINN#99999999
          PRINTSTRING("  INF.")
          ->A45
A47:      PRINT(MINN,4,2)
          SPACES(4)
          PRINT(K,4,0)
A45:      NEWLINE
      %repeat
      NEWLINE
      ->C10
   %end
%end %of %program
```

APPENDIX D

Workability criteria based on weather records for 24 years

WORKABILITY RECORD

(24 years)

Number of years

1. 24

Days																							
1	2	1	2	1	0	0	1	2	1	1	1	2	2	1	1	2	1	2	1	1	2	2	0	0
2	2	1	2	1	1	0	1	0	1	2	1	2	2	1	2	0	1	0	1	2	2	0	0	0
3	0	1	2	2	1	0	1	1	2	1	1	2	2	1	2	2	2	0	1	2	2	2	0	0
4	0	1	2	2	1	0	1	1	2	1	1	2	1	2	2	0	2	0	1	2	2	0	0	0
5	0	2	2	1	1	0	2	1	2	2	1	2	1	0	2	0	2	1	2	1	0	0	0	0
6	0	2	2	2	2	0	2	1	2	1	0	1	1	0	2	0	1	1	2	2	1	0	2	0
7	1	1	2	1	2	1	2	1	0	1	2	2	1	0	1	0	1	1	0	2	2	1	2	0
8	0	2	1	1	0	1	2	1	0	2	2	1	1	0	2	1	2	2	0	1	0	0	2	1
9	0	2	0	1	0	1	2	1	1	2	1	1	1	0	0	2	2	0	0	2	1	1	2	1
10	1	2	0	2	0	1	1	1	2	2	1	2	1	0	0	2	2	0	2	2	1	1	2	0
11	2	2	1	1	0	2	1	1	2	2	1	0	1	0	0	1	1	0	1	1	2	1	2	0
12	0	2	1	2	0	2	1	2	0	2	1	0	1	0	0	2	1	2	1	1	1	1	2	0
13	1	2	1	2	0	1	1	2	0	1	2	0	1	0	0	2	0	2	1	2	2	2	2	2
14	1	2	1	1	0	1	1	0	0	2	2	2	2	0	0	1	0	1	0	2	2	1	1	2
15	1	2	1	1	0	2	1	2	1	0	1	2	2	0	0	1	2	2	2	1	2	1	1	2
16	2	2	1	1	0	1	1	0	2	0	2	0	1	0	0	2	1	2	2	1	0	2	1	2
17	1	2	1	1	0	1	2	0	0	0	1	0	1	0	0	2	1	1	2	1	2	1	2	2
18	2	2	2	2	1	1	2	0	0	0	2	0	2	0	1	0	2	2	2	1	0	1	2	2
19	1	2	1	1	1	1	2	1	0	0	2	0	1	1	0	0	2	2	0	1	0	1	1	1
20	2	2	1	1	2	1	2	1	0	1	2	0	2	2	0	0	2	2	0	2	0	2	2	1
21	1	2	1	1	1	2	2	1	0	2	2	0	0	1	0	0	2	2	0	2	2	2	1	2
22	1	2	1	1	1	2	2	1	0	1	2	2	0	2	0	0	2	2	1	2	1	2	1	2
23	1	2	1	1	0	1	2	1	2	1	2	0	0	0	0	0	1	0	1	1	2	2	2	2
24	1	0	1	1	1	1	1	1	2	2	0	0	2	0	0	1	1	1	2	2	1	2	2	2
25	1	0	1	1	2	2	2	1	2	1	0	0	0	0	0	1	2	1	1	1	2	0	2	1
26	2	0	1	1	0	2	2	2	1	0	0	0	0	0	0	0	2	2	1	1	2	0	2	0
27	2	1	2	2	0	0	2	2	2	1	1	0	0	0	0	1	2	0	1	2	1	1	2	0
28	0	1	1	1	2	0	1	1	1	1	0	0	1	0	0	1	1	0	1	2	1	1	2	0
29	0	1	2	0	1	0	2	2	2	2	0	1	0	0	0	1	1	2	2	0	1	1	2	1
30	2	0	0	0	1	0	1	2	0	1	0	0	2	0	2	1	2	0	2	0	1	2	1	2
31	1	0	1	0	1	1	2	0	1	2	1	1	2	2	0	1	1	0	2	0	1	1	2	1
32	2	0	0	0	1	1	2	0	0	0	1	2	2	2	2	1	2	0	1	0	0	2	2	0
33	1	1	0	0	1	2	2	0	0	0	1	0	1	0	1	2	2	0	2	0	0	1	2	0
34	2	0	0	0	1	2	2	0	2	0	1	0	1	1	2	2	2	0	1	0	2	1	1	0
35	2	0	1	2	1	0	2	0	2	0	1	0	2	2	1	1	2	0	1	0	2	2	0	0
36	2	0	1	1	2	2	1	0	0	0	1	0	2	0	1	1	2	0	1	0	2	2	0	0
37	2	0	1	1	2	0	2	0	0	0	1	0	2	2	1	2	2	0	1	0	2	2	1	0
38	2	0	0	1	2	0	1	0	0	0	1	0	2	2	1	2	1	1	1	0	2	0	0	0
39	2	0	0	1	2	0	1	2	1	0	2	1	2	0	1	1	2	2	1	0	2	0	0	0
40	2	2	0	1	2	1	1	2	1	0	2	2	2	0	1	2	2	2	1	0	1	0	0	2
41	1	1	2	1	1	1	1	2	0	1	2	0	1	0	2	0	2	0	1	0	1	2	0	1
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45	2	1	1	1	1	1	1	1	0	1	0	1	0	0	0	0	2	2	2	2	1	1	2	1
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71	0	1	2	2	1	1	1	1	2	0	2	1	1	0	2	2	2	2	0	2	0	0	2	2
72	0	2	0	2	1	2	2	1	2	1	2	1	1	0	1	2	2	0	0	1	0	0	2	0
73	1	1	0	0	1	1	2	2	2	1	2	1	1	0	2	2	2	0	0	1	0	0	2	1
74	1	1	0	2	2	1	2	1	1	1	1	1	1	0	2	2	0	0	0	1	0	0	2	2
75	1	1	0	1	2	1	2	0	1	2	2	2	1	0	1	0	2	0	0	0	1	0	2	1
76	2	1	0	1	1	2	2	0	2	2	2	2	1	0	2	2	0	0	0	0	2	0	2	1
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78	2	2	1	2	2	1	1	0	0	2	2	2	1	2	2	1	0	0	0	2	2	2	2	1
79	1	2	2	0	2	2	1	0	0	1	2	1	1	2	2	0	0	0	0	0	0	2	0	2
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82	1	2	1	0	0	2	1	0	1	1	1	1	1	1	0	1	0	0	1	0	2	1	0	0
83	1	1	0	0	0	1	2	0	2	1	2	1	1	2	0	0	0	0	2	0	0	1	0	0
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85	1	1	0	1	0	0	2	0	1	2	2	2	1	1	2	0	0	0	0	0	1	1	0	0
86	1	2	0	2	1	0	2	0	1	1	2	2	2	1	1	0	0	0	0	0	2	1	0	0
87	2	2	2	2	1	1	2	1	2	2	1	1	1	1	2	0	1	0	0	0	2	2	0	0
88	0	0	0	2	1	1	1	1	2	0	2	0	2	1	2	0	1	0	0	0	1	1	2	2
89	0	0	0	2	1	1	1	1	2	0	2	2	2	1	2	0	0	0	0	0	1	1	2	2
90	0	0	0	2	1	2	1	0	2	0	1	0	2	1	1	0	0	0	1	0	1	2	2	2
91	1	0	0	1	1	1	2	0	1	1	1	0	0	1	2	0	0	0	0	1	1	2	2	1
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96	2	0	0	1	2	1	2	2	1	0	2	2	0	2	2	2	2	1	0	2	1	0	1	2
97	2	0	1	1	2	2	2	1	1	2	1	0	0	1	1	2	2	1	0	1	1	0	2	2
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100	2	0	0	1	0	0	2	1	1	0	1	0	1	1	2	2	2	2	0	1	2	1	2	2
101	2	1	0	2	0	0	1	1	2	1	1	0	1	2	2	2	2	2	0	1	2	1	1	2
102	2	2	0	1	0	0	1	1	1	1	1	0	1	2	0	2	2	1	0	1	2	1	1	2
103	2	2	0	0	1	1	1	1	2	1	1	1	1	1	2	2	1	2	0	2	1	1	1	2
104	2	1	0	0	2	1	2	1	2	1	1	0	1	1	0	2	1	1	0	2	1	1	1	2
105	1	1	0	1	1	1	1	1	2	1	2	1	1	1	0	1	1	1	1	1	1	1	1	1
106	1	2	2	2	0	1	1	2	1	2	2	1	1	1	0	1	2	1	1	2	1	1	2	1
107	1	2	0	2	0	2	1	2	1	2	2	1	2	1	0	2	2	1	1	1	1	1	2	2
108	1	0	0	0	0	2	1	0	1	1	2	1	2	1	0	2	1	1	2	1	1	1	1	2
109	2	2	0	0	0	2	2	0	1	2	1	1	2	1	2	2	1	1	2	1	1	1	2	2
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112	2	1	2	0	2	0	1	0	0	0	2	1	0	1	0	1	2	1	2	2	2	2	0	1
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116	2	1	2	2	2	2	2	2	1	0	2	2	1	1	1	2	2	2	1	1	1	1	1	1
117	2	1	2	2	0	1	1	2	1	0	1	1	1	2	1	1	0	0	2	2	2	1	0	1

118	2	1	1	1	0	1	1	2	0	1	1	2	2	2	2	1	0	2	2	1	1	1	0	1
119	1	1	1	2	0	1	1	2	0	1	2	2	1	1	2	1	0	2	2	2	1	1	0	1
120	1	1	2	2	1	1	1	1	1	1	2	2	2	2	0	2	2	2	1	1	2	1	0	1
121	0	1	1	1	1	1	2	0	1	2	1	2	1	0	0	2	0	1	2	1	1	1	0	1
122	2	1	1	2	2	1	2	0	0	2	1	2	1	0	0	2	0	1	1	1	2	2	0	1
123	2	1	1	2	0	1	2	0	0	1	1	2	2	1	1	2	0	2	2	1	2	0	2	2
124	0	2	1	2	0	2	2	0	0	1	1	2	0	2	1	2	0	2	1	1	2	2	1	1
125	2	1	2	0	1	2	2	0	0	2	1	0	0	0	1	1	1	0	2	1	2	0	2	1
126	0	2	2	0	2	2	2	2	0	1	2	0	0	2	1	1	0	1	2	2	2	0	2	1
127	0	1	0	0	0	2	0	1	0	2	2	0	0	1	2	2	0	1	2	2	2	1	2	1
128	1	1	2	2	0	2	0	1	0	2	2	0	0	1	0	1	0	1	2	2	1	1	2	1
129	2	2	2	0	2	1	2	0	0	2	1	0	0	2	0	1	1	1	1	1	2	1	2	2
130	1	2	0	0	1	1	2	0	0	1	1	1	0	2	0	1	1	2	2	1	2	1	2	1
131	1	0	2	0	1	0	0	0	0	1	1	0	0	2	2	2	2	2	2	1	1	1	2	1
132	1	1	0	1	1	0	2	0	0	1	1	0	0	2	0	2	0	2	2	1	1	1	2	1
133	1	1	0	1	1	2	2	0	0	1	1	0	0	2	1	1	0	2	1	1	1	1	2	1
134	1	1	1	1	2	2	2	0	0	2	2	0	2	1	2	1	1	1	2	1	1	1	2	1
135	1	2	1	1	1	1	2	0	0	1	2	1	1	1	1	2	1	1	2	1	2	1	2	1
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294	0	1	0	1	2	2	0	1	1	1	0	1	2	1	1	1	2	2	1	0	1	2	1	0
295	0	1	2	2	2	2	2	1	2	1	0	1	1	1	2	2	2	1	1	0	1	1	2	0
296	2	2	1	1	2	1	2	1	2	2	0	1	2	1	2	2	2	2	1	0	2	2	2	0
297	0	2	1	2	1	2	0	1	1	2	0	2	2	2	1	1	2	2	2	0	1	2	1	0
298	0	2	1	2	1	1	0	1	1	2	2	1	2	1	1	2	1	2	2	0	1	2	1	2
299	0	2	1	1	2	2	0	2	1	2	1	1	2	2	1	1	2	1	1	0	2	2	2	1
300	1	2	1	1	2	2	0	2	1	2	1	2	2	1	1	2	2	1	2	0	2	1	2	2
301	2	1	2	1	0	2	1	2	1	2	1	2	2	1	1	2	1	1	2	0	0	1	1	2
302	2	2	1	1	0	1	1	2	1	0	1	2	1	2	2	2	2	2	2	1	0	2	2	2
303	2	0	1	1	0	1	2	0	1	2	2	1	1	0	1	1	2	2	2	1	0	0	2	0
304	2	0	2	1	0	2	2	0	1	0	1	1	1	0	2	2	2	2	2	1	0	0	2	0
305	0	0	2	1	2	0	0	2	2	2	1	2	1	2	1	2	2	0	2	1	0	0	2	0
306	0	0	2	2	1	1	0	1	0	2	2	2	1	0	2	2	2	0	2	1	2	0	1	0
307	0	0	0	2	1	2	1	1	2	0	2	1	1	0	2	2	2	0	2	1	2	1	1	0
308	0	2	2	1	1	2	1	1	1	0	0	1	2	0	1	2	2	0	2	2	1	2	1	2
309	2	0	0	1	1	0	1	2	2	1	0	1	1	0	1	2	2	0	2	2	1	0	1	1

310	2	0	0	1	2	0	1	1	2	2	0	2	1	1	1	2	2	1	1	0	1	0	1	2
311	0	0	0	1	2	2	1	2	0	2	0	2	2	0	1	2	2	2	2	0	1	0	1	2
312	1	0	0	1	1	1	2	2	0	2	0	2	2	0	1	1	2	1	2	0	1	1	1	2
313	1	0	0	1	1	1	1	2	0	2	1	2	2	0	2	1	2	1	2	0	2	2	1	2
314	2	0	0	2	1	1	2	2	0	0	1	2	2	0	2	1	2	2	2	0	2	0	2	1
315	1	0	2	2	2	2	2	2	0	0	2	2	2	2	1	1	0	1	2	1	2	0	1	2
316	0	0	2	2	2	2	0	1	0	0	2	2	2	2	1	1	0	0	1	1	1	0	1	1
317	0	2	2	0	2	2	0	1	1	0	1	1	2	2	1	1	2	0	2	0	1	0	1	1
318	0	2	2	0	1	2	0	1	0	0	1	1	2	2	2	2	0	2	2	0	1	1	1	1
319	1	1	2	0	2	2	1	1	2	0	2	2	1	1	0	2	2	0	2	0	2	0	1	2
320	1	0	1	0	2	1	1	2	1	0	1	1	1	2	0	1	0	2	2	0	2	0	1	2
321	1	2	2	1	2	2	1	1	1	0	0	1	2	2	1	2	0	2	0	0	0	0	1	2
322	1	1	2	0	2	2	1	1	1	0	0	2	2	2	2	1	0	2	0	0	0	0	1	2
323	1	1	0	1	2	2	1	1	2	0	1	2	1	2	2	1	0	2	1	0	0	2	2	2
324	1	1	0	1	2	2	1	2	2	0	0	2	1	2	1	1	0	2	1	0	2	2	1	2
325	1	1	0	1	1	2	1	2	0	0	0	2	1	0	1	2	0	2	2	0	2	2	1	2
326	2	2	2	2	2	2	1	2	2	1	0	1	2	0	2	1	0	0	2	0	0	0	1	2
327	0	2	2	2	2	2	1	2	2	0	0	1	2	0	2	1	0	0	0	0	0	0	1	2
328	0	2	2	2	2	2	1	2	1	1	0	1	1	0	2	2	0	0	0	0	1	2	2	2
329	0	1	2	1	1	2	2	2	1	2	1	1	1	1	2	2	1	1	0	2	0	1	2	2
330	0	1	1	2	2	2	2	2	1	0	2	1	1	0	2	2	1	1	1	2	0	2	2	2
331	0	1	2	0	1	2	2	2	2	0	1	2	1	0	2	2	1	1	2	2	0	1	2	2
332	0	1	2	0	2	1	1	2	1	0	1	2	2	0	2	2	1	1	2	1	0	1	2	2
333	0	2	1	1	2	0	2	2	1	0	2	0	1	0	2	2	1	2	2	1	0	1	1	2
334	0	1	2	2	1	0	1	2	2	0	1	0	1	0	2	1	2	2	2	1	0	1	1	1
335	1	2	1	2	2	0	1	1	1	0	1	0	1	0	0	2	2	2	2	1	0	1	1	0
336	1	1	1	2	2	0	2	1	2	0	1	1	2	1	2	1	1	2	2	1	2	2	2	0
337	1	2	1	1	2	1	1	2	1	2	2	2	1	0	1	2	2	2	2	2	0	1	2	0
338	0	1	1	2	2	1	1	2	1	2	1	0	2	0	1	2	1	2	2	2	0	2	2	0
339	0	1	1	2	2	2	1	2	1	2	1	0	2	0	1	2	1	1	2	2	0	1	1	0
340	1	1	2	0	2	2	1	2	2	2	1	0	1	2	1	0	2	1	2	1	2	1	1	0
341	1	2	2	0	1	0	1	1	1	1	2	0	0	2	1	0	2	0	0	1	1	2	2	0
342	0	2	1	2	2	0	2	1	1	1	2	1	1	0	1	2	2	0	2	2	1	2	2	0
343	0	1	1	2	0	0	1	1	1	1	1	0	2	0	1	1	2	0	2	2	1	2	1	0
344	0	2	1	2	0	1	2	2	2	1	1	0	0	2	1	1	0	0	2	2	1	1	1	1
345	2	2	2	0	2	0	2	1	1	1	2	0	0	2	2	0	0	0	2	2	1	1	2	1
346	2	2	1	0	2	0	1	1	1	1	2	2	0	2	1	0	2	0	2	2	1	2	2	1
347	2	2	2	0	2	0	1	1	2	2	2	2	0	2	1	2	1	2	1	2	0	2	2	2
348	1	2	1	1	0	2	1	1	2	1	0	2	1	2	1	2	1	0	2	2	0	2	2	2
349	1	2	1	2	2	0	2	1	2	1	1	1	2	2	1	2	1	0	2	2	0	2	1	1
350	1	1	1	0	2	1	1	2	1	2	2	2	1	0	1	2	1	1	2	2	1	2	2	2
351	1	2	1	1	2	0	1	2	2	2	1	2	1	2	2	2	2	1	2	2	1	1	0	2
352	1	2	1	1	2	0	1	2	2	2	2	1	1	2	1	1	2	1	1	2	1	2	2	2
353	1	2	1	2	1	0	1	2	2	2	0	1	2	2	1	0	1	1	1	2	1	2	0	0
354	1	2	1	2	2	1	2	2	2	1	0	1	0	2	1	0	1	2	1	2	2	2	0	0
355	1	2	1	0	2	1	2	2	2	1	0	1	2	0	1	0	2	0	1	2	2	1	0	2
356	2	1	1	0	0	2	0	2	1	1	0	1	0	0	1	0	2	0	1	2	1	1	0	0
357	1	2	1	1	0	2	2	1	2	0	0	1	1	2	2	1	0	2	2	2	0	2	0	0
358	1	2	2	1	0	1	0	2	2	0	1	1	1	2	2	2	0	0	1	2	0	1	0	0
359	2	2	2	1	0	2	0	2	1	0	2	2	2	0	1	1	0	0	2	2	0	2	0	2
360	2	1	2	2	1	2	1	1	1	0	0	1	1	0	1	1	0	0	2	1	1	2	0	1
361	1	2	1	1	1	2	1	1	1	0	0	2	2	0	1	1	2	0	2	2	2	2	0	1
362	2	1	1	0	1	2	2	1	1	0	2	2	2	0	1	2	2	0	2	2	0	2	0	2
363	1	2	2	0	2	2	1	2	1	0	1	2	2	1	1	2	1	0	1	2	0	2	0	2
364	1	2	2	0	2	2	1	1	1	0	1	1	2	2	2	2	1	0	1	2	0	2	0	2
365	2	2	1	0	0	2	1	1	1	1	1	1	2	2	2	1	2	0	2	2	0	0	0	1
366	0				0				0				0				0				0			

APPENDIX E

Markov model

MARKOV MODEL

```
%begin
   %integer %array W(0:365,0:24)
   %integer %array A(0:1,0:1),TX(0:2)
   %integer %array AP(1:2,0:2),TY(0:3)
   %integer I,J,M,N,S,K
   SELECT INPUT(1)
   SELECT OUTPUT(2)
   %cycle I = 1,1,365
      %cycle J = 0,1,24
         READ(W(I,J))
      %repeat
   %repeat
   %cycle J = 0,1,24
      W(0,J) = W(365,J)
   %repeat
   %cycle N = 0,1,1
      %cycle M = 0,1,1
         A(M,N) = 0
      %repeat
   %repeat
   %cycle N = 0,1,2
      TX(N) = 0
   %repeat
   %cycle N = 0,1,2
      %cycle M = 1,1,2
         AP(M,N) = 0
      %repeat
   %repeat
   %cycle N = 0,1,3
      TY(N) = 0
   %repeat
   %routine COUNT(%integer S,K, %integer %array %name DATA,TX)
      %cycle N = 0,1,1
         TX(N) = 0
      %repeat
      %cycle J = 1,1,24
         %cycle I = S,1,K
            %if W(I-1,J)>0 %then ->A2
            N = 0
            %if W(I,J)>0 %then ->A1
            M = 0
            ->A5
A1:         M = 1
            ->A5
A2:         N = 1
            %if W(I,J)>0 %then ->A3
            M = 0
            ->A5
A3:         M = 1
A5:         DATA(M,N) = DATA(M,N)+1
         %repeat
      %repeat
      %cycle N = 0,1,1
         %cycle M = 0,1,1
            TX(N) = TX(N)+A(M,N)
         %repeat
      %repeat
      TX(2) = TX(0)+TX(1)
      %cycle M = 0,1,1
         %cycle N = 0,1,1
```

```
            WRITE(DATA(M,N),4)
            SPACES(2)
         %repeat
         NEWLINE
      %repeat
      NEWLINE
      %cycle N = 0,1,2
         WRITE(TX(N),4)
      %repeat
      NEWLINE
   %end
   %routine COUNT2(%integer S,K, %integer %array %name DATA1,TY)
      %cycle N = 0,1,2
         TY(N) = 0
      %repeat
      %cycle J = 1,1,24
         %cycle I = S,1,K
            %if W(I-1,J)>0 %then ->B2
            N = 0
            %if W(I,J)<1 %then ->B7
            %if W(I,J)>1 %then ->B1
            M = 1
            ->B6
B1:         M = 2
            ->B6
B2:         %if W(I-1,J)>1 %then ->B4
            N = 1
            %if W(I,J)<1 %then ->B7
            %if W(I,J)>1 %then ->B3
            M = 1
            ->B6
B3:         M = 2
            ->B6
B4:         N = 2
            %if W(I,J)<1 %then ->B7
            %if W(I,J)>1 %then ->B5
            M = 1
            ->B6
B5:         M = 2
B6:         DATA1(M,N) = DATA1(M,N)+1
B7:      %repeat
      %repeat
      %cycle N = 0,1,2
         %cycle M = 1,1,2
            TY(N) = TY(N)+DATA1(M,N)
         %repeat
      %repeat
      TY(3) = TY(0)+TY(1)+TY(2)
      %cycle M = 1,1,2
         %cycle N = 0,1,2
            WRITE(DATA1(M,N),4); SPACES(2)
         %repeat
         NEWLINE
      %repeat
      NEWLINE
      %cycle N = 0,1,3
         WRITE(TY(N),4); SPACES(2)
      %repeat
   %end
   S = 218
   K = 249
   COUNT(S,K,A,TX)
   COUNT2(S,K,AP,TY)
%end %of %program
```

APPENDIX F

Simulation model

INPUT DATA FOR SIMULATION

Frequency of work and non work days for each period.
(Markov process)

Period A

20	22		
20	706		
40	728	768	
10	230	120	
10	124	232	
20	354	352	726

Period B

39	20		
18	331		
57	351	408	
11	100	55	
7	66	110	
18	166	165	349

Period C

112	56		
56	448		
168	504	672	
32	129	74	
24	89	156	
56	218	230	504

Period D

178	65		
68	697		
246	762	1008	
34	198	111	
34	132	256	
68	330	367	765

Period E

102	51		
48	495		
150	546	696	
23	144	84	
25	94	173	
48	238	257	543

Periof F

291	111		
112	998		
403	1109	1512	
65	343	165	
47	193	297	
112	536	462	1110

Period G

153	50		
46	423		
199	473	672	
26	145	74	
20	85	119	
46	230	193	469

Period H

184	77		
81	834		
265	911	1176	
43	346	124	
38	146	218	
81	492	342	915

Period I

95	60		
63	1630		
158	1690	1848	
26	622	275	
37	281	452	
63	903	727	1693

Area for each crop of the rotation.

100
50
50
50

Maximum yield given by each crop.

8.0
8.0
7.0
45

Early and late planting and harvesting coefficients for each crop.

0.533	0.00573	-0.306	0.00019	0.045	0.00587
0.676	0.00574	-0.522	0.00338	0.0189	0.00587
0.691	0.00828	-0.649	0.00183	0.0189	0.00587
0.659	0.00555	-0.766	0.00380	0.0000	0.0000

Optimum planting and harvesting dates for each crop.

296
260
78
104
267
219
250
281

Number and rate of work of each item of implement used.

0 .62
2 .8
0 .92
0 1.9
0 2.5
1 3.2
0 4.8
0 1.5
0 1.9
2 2.5
0 3.8
1 .5
0 .6
0 .3
0 .4
1 .6
1 1.3
1 1.55
2 .3

Initial number of hectares and date of planting for each crop

40 260
40 262
20 264
4.8 104
4.8 105
4.8 106
4.8 107
4.8 108
4.8 109
4.8 110
4.8 111
4.8 112
4.8 113
2.0 114
40 78
10 80
40 296
10 298

SIMULATION MODEL

```
%begin
   %external %real %fn %spec RANDOM(%integer %name IX, %integer N)
   %integer I,J,KP,P,Q,DP,PP,PQ,NY,IX,SS,KK,FLAG,WP,WQ
   %real X,D,Z1,Z2,YYY,ZZZ,XXX,AH,AP,AC,AD,RW,R,TR,RC,RP,RD,WBY,CYB,CPY,SBY,
      STD,STH,STP,STC,WWY,PXX,PHMAX,AL,RL,PHY,AS,STPL,STS,RPL,RS,APL,SBAN,
      SBTSP,PAN,PTSP,WBAN,WBTSP,H,RH,BAH
   %real %array Y(1:4),K(1:6,1:4),WB(1:20,0:15),M1,M2(1:4,0:1),L(1:4),
      SB(1:20,0:15),WW(1:20,0:15),PH(1:20,0:15),RES(0:100,1:4),NWB(1:20,
      0:15),NWW(1:20,0:15),M,M4(1:3,0:1),M3,M5(1:2,0:1),M6(0:1)
   %integer %array W(0:366),T(0:1,1:4)
   %integer %array AA,BB,CC,DD,EE,FF,GG,HH,II(0:1,0:1)
   %integer %array AAP,BBP,CCP,DDP,EEP,FFP,GGP,HHP,IIP(1:2,0:2)
   %integer %array TAA,TBB,TCC,TDD,TEE,TFF,TGG,THH,TII(0:2)
   %integer %array TA1,TB1,TC1,TD1,TE1,TF1,TG1,TH1,TI1(0:3)
   %routine LESEN(%integer %array %name DATA,DATA1,TX,TX1)
      %integer M,N
      %cycle M = 0,1,1
         %cycle N = 0,1,1
            READ(DATA(M,N))
         %repeat
      %repeat
      %cycle N = 0,1,2
         READ(TX(N))
      %repeat
      %cycle M = 1,1,2
         %cycle N = 0,1,2
            READ(DATA1(M,N))
         %repeat
      %repeat
      %cycle N = 0,1,3
         READ(TX1(N))
      %repeat
   %end
   %routine DAYS(%integer %array %name W,DATA,DATA1,TX,TX1, %integer SS,KK)
      %integer I,P,N
      %cycle I = SS,1,KK
         Z1 = RANDOM(IX,1)
         P = 0
         N = W(I-1)
         %if N=0 %then ->M0
         P = 1
M0:      %if Z1>DATA(0,P)/TX(P) %then ->M1
         W(I) = 0
         ->M5
M1:      W(I) = 1
         Z2 = RANDOM(IX,1)
         %if Z2>DATA1(1,N)/TX1(N) %then ->M2
         ->M5
M2:      W(I) = 2
M5:   %repeat
   %end
   SELECT INPUT(1)
   SELECT OUTPUT(2)
!READ IN MATRICES.
   LESEN(AA,AAP,TAA,TA1)
   LESEN(BB,BBP,TBB,TB1)
   LESEN(CC,CCP,TCC,TC1)
   LESEN(DD,DDP,TDD,TD1)
   LESEN(EE,EEP,TEE,TE1)
```

```
   LESEN(FF,FFP,TFF,TF1)
   LESEN(GG,GGP,TGG,TG1)
   LESEN(HH,HHP,THH,TH1)
   LESEN(II,IIP,TII,TI1)
   IX = 7
   NY = 0
   Z1 = RANDOM(IX,1)
!
!
!
!INITIALIZE MATRIX
   %cycle I = 1,1,20
      %cycle J = 0,1,15
         WB(I,J) = 0
         SB(I,J) = 0
         WW(I,J) = 0
         PH(I,J) = 0
         NWB(I,J) = 0
         NWW(I,J) = 0
      %repeat
   %repeat
!READ CROP AREA.
   %cycle J = 1,1,4
      READ(L(J))
   %repeat
!READ IN THE EXPECTED YIELDS WITHOUT PENALTIES.
   %cycle J = 1,1,4
      READ(Y(J))
   %repeat
!
!READ IN TIMELINESS PENALTIES.
   %cycle J = 1,1,4
      %cycle I = 1,1,6
         READ(K(I,J))
      %repeat
   %repeat
!
!
!READ IN OPTIMAL DATES OF SOWING AND HARVESTING.
   %cycle I = 0,1,1
      %cycle J = 1,1,4
         READ(T(I,J))
      %repeat
   %repeat
!
!
!READ IN MACHINE RATES OF WORK.
   %cycle I = 1,1,3
      %cycle J = 0,1,1
         READ(M(I,J))
      %repeat
   %repeat
   %cycle I = 1,1,4
      %cycle J = 0,1,1
         READ(M1(I,J))
      %repeat
   %repeat
   %cycle I = 1,1,4
      %cycle J = 0,1,1
         READ(M2(I,J))
      %repeat
   %repeat
   %cycle I = 1,1,2
      %cycle J = 0,1,1
```

```
          READ(M3(I,J))
       %repeat
    %repeat
    %cycle I = 1,1,3
       %cycle J = 0,1,1
          READ(M4(I,J))
       %repeat
    %repeat
    %cycle I = 1,1,2
       %cycle J = 0,1,1
          READ(M5(I,J))
       %repeat
    %repeat
    %cycle J = 0,1,1
       READ(M6(J))
    %repeat

 !READ IN INITIAL DATA WINTER BARLEY
    %cycle I = 1,1,3
       %cycle J = 0,1,1
          READ(WB(I,J))
       %repeat
    %repeat
 !READ IN INITIAL DATA POTATOES
    %cycle I = 1,1,11
       %cycle J = 0,1,1
          READ(PH(I,J))
       %repeat
    %repeat
 !READ IN INITIAL DATA SPRING BARLEY
    %cycle I = 1,1,2
       %cycle J = 0,1,1
          READ(SB(I,J))
       %repeat
    %repeat
 !
 !READ IN INITIAL DATA WINTER WHEAT
    %cycle I = 1,1,2
       %cycle J = 0,1,1
          READ(WW(I,J))
       %repeat
    %repeat
    IX = 7
!TEMPORARY SIMULATOR
    %cycle KP = 1,1,366
       Z1 = RANDOM(IX,1)
       %if Z1>0.3333 %then ->A5
       W(KP) = 0
       %continue
A5:    Z2 = RANDOM(IX,1)
       %if Z2>.3333 %then ->A6
       W(KP) = 1
       %continue
A6:    W(KP) = 2
    %repeat
!
    RP = 0
    RD = 0
    RC = 0
    H = 0
    RS = 0
    RPL = 0
    RH = 0
!ALL RATE OF WORK CALCULATION
```

```
    %cycle I = 1,1,3
       %if M(I,0)=0 %then %continue
       RP = RP+M(I,1)*M(I,0)
    %repeat
    %cycle I = 1,1,4
       %if M1(I,0)=0 %then %continue
       RC = RC+M1(I,1)*M1(I,0)
    %repeat
    %cycle I = 1,1,4
       %if M2(I,0)=0 %then %continue
       RD = RD+M2(I,1)*M2(I,0)
    %repeat
    %cycle I = 1,1,2
       %if M3(I,0)=0 %then %continue
       RS = RS+M3(I,1)*M3(I,0)
    %repeat
    %cycle I = 1,1,3
       %if M4(I,0)=0 %then %continue
       RPL = RPL+M4(I,1)*M4(I,0)
    %repeat
    %cycle I = 1,1,2
       %if M5(I,0)=0 %then %continue
       H = H+M5(I,1)*M5(I,0)
    %repeat
    RH = M6(1)*M6(0)
 YEAR:
    Q = 0
    P = 1
    TR = 0
    AH = 0
    AP = 0
    AC = 0
    XXX = 0
    SS = 218
    KK = 249
    DAYS(W,AA,AAP,TAA,TA1,SS,KK)
    %cycle I = 1,1,20
       XXX = XXX+WB(I,0)
    %repeat
 !
    R = WB(P,0)
    %cycle I = 218,1,249
       TR = 6
       %if W(I)<1 %then ->CU5
       %if W(I)<2 %then ->PL0
HA0:   %if AH>=XXX-0.1 %then ->PL1
       %if R<=0 %then ->HA2
       ->HA3
HA2:   P = P+1
       Q = 0
       R = WB(P,0)
HA3:   %if TR<0.1 %then ->CU5
       %if R>TR*H %then ->R1
       AH = AH+R
       TR = TR-R/H
       WB(P,Q+3) = R
       WB(P,Q+4) = I
       R = 0
       Q = Q+2
       ->HA0
R1:    AH = AH+TR*H
       WB(P,Q+3) = TR*H
       WB(P,Q+4) = I
       R = R-TR*H
```

```
       Q = Q+2
       ->CU5
 PL0:  TR = 8
 PL1:  %if TR<8 %then ->PL0
       %if AH<=AP %then ->CU1
       %if AH-AP>TR*RP %then ->PL2
       TR = TR-(AH-AP)/RP
       AP = AH
       ->CU1
 PL2:  AP = AP+TR*RP
       ->CU5
 CU1:  %if AP<=AC %then ->CU5
       %if AP-AC>TR*RC %then ->CU2
       AC = AP
       ->CU5
 CU2:  AC = AC+TR*RC
 CU5: %repeat
    %cycle I = 1,1,20
       %unless WB(I,0)>0 %then %continue
       D = T(0,2)-WB(I,1)
       %if D<0 %then ->A4
       X = (K(1,2)*D+K(2,2)*D*D)/100
       WB(I,2) = Y(2)*(1-X)
       %continue
 A4:   X = (K(3,2)*D+K(4,2)*D*D)/100
       WB(I,2) = Y(2)*(1-X)
    %repeat
    CYB = 0
    CPY = 0
!WINTER BARLEY HARVESTING LOSSES.
    %cycle I = 1,1,20
       %unless WB(I,0)>0 %then %continue
       %cycle J = 3,2,9
          D = WB(I,J+1)-T(1,2)
          %if D<0 %then ->B1
          X = (1.72+K(5,2)*D+K(6,2)*D*D)/100
          WBY = WB(I,2)*(1-X)
          ->B2
B1:       WBY = WB(I,2)
B2:       CYB = CYB+WB(I,J)*WBY
       %repeat
       CPY = CPY+WB(I,2)*WB(I,0)
    %repeat
    RES(NY,2) = Y(2)*XXX-CYB
    Q = 0
    P = 1
    TR = 0
    DP = 1
    AH = 0
    AP = 0
    AC = 0
    AD = 0
    YYY = 0
    STD = 0
    WBAN = (L(1)/2)/(8*RD)
    WBTSP = INT(WBAN/0.8554)
    SS = 250
    KK = 266
    DAYS(W,BB,BBP,TBB,TB1,SS,KK)
    %cycle I = 1,1,20
      YYY = YYY+SB(I,0)
    %repeat
!
   R = SB(P,0)
```

```
%cycle I = 250,1,266
    TR = 6
    %if W(I)<1 %then ->DR6
    %if W(I)<2 %then ->PL01
HA01: %if AH>=YYY-0.1 %then ->PL10
    %if R<=0 %then ->HA21
    ->HA31
HA21: P = P+1
    Q = 0
    R = SB(P,0)
HA31: %if TR<0.1 %then ->DR6
    %if R>TR*H %then ->R11
    AH = AH+R
    TR = TR-R/H
    SB(P,Q+3) = R
    SB(P,Q+4) = I
    R = 0
    Q = Q+2
    ->HA01
R11:  AH = AH+TR*H
    SB(P,Q+3) = TR*H
    SB(P,Q+4) = I
    R = R-TR*H
    Q = Q+2
    ->DR6
PL01: TR = 8
PL10: %if TR<8 %then ->PL01
    %if AH<=AP %then ->CU11
    %if AH-AP>TR*RP %then ->PL21
    TR = TR-(AH-AP)/RP
    AP = AH
    ->CU11
PL21: AP = AP+TR*RP
    ->DR6
CU11: %if AP<=AC %then ->DR11
    %if AP-AC>TR*RC %then ->CU21
    AC = AP
    ->DR11
CU21: AC = AC+TR*RC
CU6:  ->DR6
DR11: %if I<260-WBTSP %then ->DR6
    %if (L(1)/2)+AC<=AD %then ->DR6
    %if (L(1)/2)+AC-AD>TR*RD %then ->DR21
    NWB(DP,0) = (L(1)/2)+AC-AD
    NWB(DP,1) = I
    AD = AC+(L(1)/2)
    DP = DP+1
    ->DR6
DR21: AD = AD+TR*RD
    NWB(DP,0) = TR*RD
    NWB(DP,1) = I
    DP = DP+1
DR6: %repeat
   BAH = AH
   STP = L(3)-AP
   STC = L(3)-AC
   STD = L(1)-AD
   WQ = 0
   PQ = 0
   WP = 1
   TR = 0
   PP = 1
   AL = 0
   AH = 0
```

```
    FLAG = 0
    ZZZ = 0
    PXX = 0
    PHMAX = 8*RH
    AD = 0
    SS = 267
    KK = 294
    DAYS(W,CC,CCP,TCC,TC1,SS,KK)
    %cycle I = 1,1,20
       ZZZ = ZZZ+WW(I,0)
       PXX = PXX+PH(I,0)
    %repeat
 !
    RW = WW(WP,0)
    RL = PH(PP,0)
    %cycle I = 267,1,294
       TR = 6
       %if W(I)<1 %then ->DR7
       %if W(I)<2 %then ->PL03
 SBH1: %if BAH>=YYY-0.1 %then ->HA03
       %if R<=0 %then ->SBH2
       ->SBH3
 SBH2: P = P+1
       Q = 0
       R = SB(P,0)
 SBH3: %if TR<0.1 %then ->DR7
       %if R>TR*H %then ->SR13
       BAH = BAH+R
       TR = TR-R/H
       SB(P,Q+3) = R
       SB(P,Q+4) = I
       R = 0
       Q = Q+2
       ->SBH1
 SR13: BAH = BAH+TR*H
       SB(P,Q+3) = TR*H
       SB(P,Q+4) = I
       R = R-TR*H
       Q = Q+2
       ->DR7

 PL03: %if STP<0.1 %then ->CU13
       TR = 8
 PL13: %if TR<8 %then ->PL03
       %if BAH<=AP %then ->CU13
       %if BAH-AP>TR*RP %then ->PL23
       TR = TR-(BAH-AP)/RP
       AP = BAH
       STP = YYY-BAH
       ->CU13
 PL23: AP = AP+TR*RP
 STP=STP-TR*RP
       ->DR7
 CU13: %if STC<0.1 %then ->DR13
       %if AP<=AC %then ->DR13
       %if AP-AC>TR*RC %then ->CU23
       AC = AP
       STC = STP
       ->DR13
 CU23: AC = AC+TR*RC
       STC = STC-TR*RC
       ->DR7
 DR13: %if STD<0.1 %then ->POT1
       %if STD<=AD %then ->POT1
```

```
       %if STD-AD>TR*RD %then ->DR23
       NWB(DP,0) = STD-AD
       NWB(DP,1) = I
       AD = STD
       DP = DP+1
       ->POT1
DR23:  AD = AD+TR*RD
       NWB(DP,0) = TR*RD
       NWB(DP,1) = I
       DP = DP+1
       ->DR7
HA03:  %if AH>=ZZZ-0.1 %then ->PL13
       %if RW<=0 %then ->HA23
       ->HA33
HA23:  WP = WP+1
       WQ = 0
       RW = WW(WP,0)
HA33:  %if TR<0.1 %then ->DR7
       %if RW>TR*H %then ->R13
       AH = AH+RW
       TR = TR-RW/H
       WW(WP,WQ+3) = RW
       WW(WP,WQ+4) = I
       RW = 0
       WQ = WQ+2
       ->HA03
R13:   AH = AH+TR*H
       WW(WP,WQ+3) = TR*H
       WW(WP,WQ+4) = I
       RW = RW-TR*H
       WQ = WQ+2
       ->DR7
POT1:  %if AL>=PXX-0.1 %then ->DR7
       %if RL<=0 %then ->POT2
       ->POT3
POT2:  PP = PP+1
       PQ = 0
       RL = PH(PP,0)
POT3:  %if TR<0.1 %then ->DR7
       %if RL>TR*RH %then ->S1
       AL = AL+RL
       TR = TR-RL/RH
       PH(PP,PQ+3) = RL
       PH(PP,PQ+4) = I
       RL = 0
       ->POT1
S1:    AL = AL+TR*RH
       PH(PP,PQ+3) = TR*RH
       PH(PP,PQ+4) = I
       RL = RL-TR*RH
       PQ = PQ+2
DR7: %repeat
   %cycle I = 1,1,20
      %cycle J = 0,1,15
         WB(I,J) = NWB(I,J)
         NWB(I,J) = 0
      %repeat
   %repeat
!SPRING BARLEY PLANTING LOSSES.
   %cycle I = 1,1,20
      %unless SB(I,0)>0 %then %continue
      D = T(0,3)-SB(I,1)
      %if D<0 %then ->A3
      X = (K(1,3)*D+K(2,3)*D*D)/100
```

```
       SB(I,2) = Y(3)*(1-X)
       %continue
 A3:   X = (K(3,3)*D+K(4,3)*D*D)/100
       SB(I,2) = Y(3)*(1-X)
    %repeat
    CYB = 0
    CPY = 0
 !SPRING BARLEY HARVESTING LOSSES.
    %cycle I = 1,1,20
       %unless SB(I,0)>0 %then %continue
       %cycle J = 3,2,9
          D = SB(I,J+1)-T(1,3)
          %if D<0 %then ->B11
          X = (1.72+K(5,3)*D+K(6,3)*D*D)/100
          SBY = SB(I,2)*(1-X)
          ->B21
 B11:     SBY = SB(I,2)
 B21:     CYB = CYB+SB(I,J)*SBY
       %repeat
       CPY = CPY+SB(I,2)*SB(I,0)
    %repeat
    RES(NY,3) = Y(3)*YYY-CYB
    %cycle I = 1,1,20
       %cycle J = 0,1,15
          SB(I,J) = 0
       %repeat
    %repeat
    TR = 0
    DP = 1
    AC = 0
    AD = 0
    STD = PXX
    STC = PXX
    STH = ZZZ-AH
    STP = 0
    PHMAX = 8*RH
    CPY = 0
    CYB = 0
    SS = 295
    KK = 336
    DAYS(W,DD,DDP,TDD,TD1,SS,KK)
    %cycle I = 295,1,336
       TR = 8
       %if W(I)<1 %then ->DR8
       %if W(I)<2 %then ->POT11
HA40:  %if FLAG=1 %then ->POT11
       %unless AH>=ZZZ-0.1 %then ->HA41
       FLAG = 1
HA41:  %if RW<=0 %then ->HA43
       ->HA44
HA43:  WP = WP+1
       WQ = 0
       RW = WW(WP,0)
HA44:  %if TR<0.1 %then ->DR8
       %if RW>TR*H %then ->R44
       AH = AH+RW
       TR = TR-RW/H
       WW(WP,WQ+3) = RW
       WW(WP,WQ+4) = I
       RW = 0
       ->HA40
R44:   AH = AH+TR*H
       WW(WP,WQ+3) = TR*H
       WW(WP,WQ+4) = I
```

```
        RW = RW-TR*H
        WQ = WQ+2
        ->DR8
 CU14:  %if AL<=AC %then ->DR14
        %if AL-AC>TR*RC %then ->CU24
        AC = AL
        ->DR14
 CU24:  AC = AC+TR*RC
 CU8:   ->DR8
 DR14:  %if AD>=PXX %then ->DR8
        %if PXX-AD>TR*RD %then ->DR24
        NWW(DP,0) = PXX-AD
        NWW(DP,1) = I
        AD = PXX
        DP = DP+1
        ->DR8
 DR24:  AD = AD+TR*RD
        NWW(DP,0) = TR*RD
        NWW(DP,1) = I
        DP = DP+1
        ->DR8
 POT11: %if AL>=PXX-0.1 %then ->CU14
        %if RL<=0 %then ->POT21
        ->POT31
 POT21: PP = PP+1
        PQ = 0
        RL = PH(PP,0)
 POT31: %if TR<0.1 %then ->DR8
        %if RL>TR*RH %then ->S11
        AL = AL+RL
        TR = TR-RL/RH
        PH(PP,PQ+3) = RL
        PH(PP,PQ+4) = I
        RL = 0
        ->POT11
 S11:       PH(PP,PQ+3) = TR*RH
        PH(PP,PQ+4) = I
        RL = RL-TR*RH
        AL = AL+TR*RH
        PQ = PQ+2
 DR8: %repeat
    %cycle I = 1,1,20
       %unless WW(I,0)>0 %then %continue
       D = T(0,1)-WW(I,1)
       %if D<0 %then ->A2
       X = (K(1,1)*D+K(2,1)*D*D)/100
       WW(I,2) = Y(1)*(1-X)
       %continue
 A2:   X = (K(3,1)*D+K(4,1)*D*D)/100
       WW(I,2) = Y(1)*(1-X)
    %repeat
    CYB = 0
    CPY = 0
!WINTER WHEAT HARVESTING LOSSES.
    %cycle I = 1,1,20
       %unless WW(I,0)>0 %then %continue
       %cycle J = 3,2,9
          D = WW(I,J+1)-T(1,1)
          %if D<0 %then ->B13
          X = (1.61+K(5,1)*D+K(6,1)*D*D)/100
          WWY = WW(I,2)*(1-X)
          ->B23
B13:      WWY = WW(I,2)
B23:      CYB = CYB+WW(I,J)*WWY
```

```
        %repeat
        CPY = CPY+WW(I,2)*WW(I,0)
     %repeat
     RES(NY,1) = Y(1)*ZZZ-CYB
     %cycle I = 1,1,20
        %cycle J = 0,1,15
           WW(I,J) = NWW(I,J)
           NWW(I,J) = 0
        %repeat
     %repeat
 !POTATOES PLANTING LOSSES.
     %cycle I = 1,1,20
        %unless PH(I,0)>0 %then %continue
        D = T(0,4)-PH(I,1)
        %if D<0 %then ->C2
        X = (K(1,4)*D+K(2,4)*D*D)/100
        PH(I,2) = Y(4)*(1-X)
        %continue
 C2:    X = (K(3,1)*D+K(4,1)*D*D)/100
        PH(I,2) = Y(4)*(1-X)
    %repeat
    CPY = 0
    CYB = 0
 !POTATOES HARVESTING LOSSES.
    %cycle I = 1,1,20
       %unless PH(I,0)>0 %then %continue
       %cycle J = 3,2,9
          D = PH(I,J+1)-T(1,4)
          %if D<0 %then ->B14
          X = (K(5,4)*D+K(6,4)*D*D)/100
          PHY = PH(I,2)*(1-X)
          ->B24
B14:      PHY = PH(I,2)
B24:      CYB = CYB+PH(I,J)*PHY
       %repeat
       CPY = CPY+PH(I,2)*PH(I,0)
   %repeat
%IF PXX<L(4) %THEN PXX=L(4)
   RES(NY,4) = Y(4)*PXX-CYB
%CYCLE I=1,1,20
%CYCLE J=0,1,15
         PH(I,J) = 0
      %repeat
   %repeat
!
!
!
AP=0
   STP = L(1)
   STD = PXX-AD
   SS = 337
   KK = 366
   DAYS(W,EE,EEP,TEE,TE1,SS,KK)
   W(0) = W(365)
   %cycle I = 337,1,365
      TR = 8
      %if W(I)<1 %then ->PL25
      %if AD>=PXX %then ->PL30
      %if PXX-AD>TR*RD %then ->DR30
      WW(DP,0) = PXX-AD
      WW(DP,1) = I
      AD = PXX
      TR = TR-WW(DP,0)/RD
      ->PL30
```

```
 DR30: AD = AD+TR*RD
       WW(DP,0) = TR*RD
       WW(DP,1) = I
       DP = DP+1
       ->PL30
 PL30: %if STP-AP<8*RP %then ->PL15
       AP = AP+TR*RP
       ->PL25
 PL15: X = STP-AP
 PL25: %repeat
    NY = NY+1
    STP = STP-AP
    AP = 0
    SS = 1
    KK = 63
    DAYS(W,FF,FFP,TFF,TF1,SS,KK)
    %cycle I = 1,1,63
       %if STP<=0 %then ->PL5
       TR = 8
       %if W(I)<1 %then ->PL4
       %if STP-AP<8*RP %then ->PL3
       AP = AP+TR*RP
       ->PL4
 PL3:  X = STP-AP
       ->PL5
 PL4: %repeat
 PL5:   AP = 0
    STP = 0
    AC = 0
    AD = 0
    STC = L(3)+L(4)
    STD = L(3)
    P = 1
    SBAN = STD/(8*RD)
    SBAN = SBAN/2
    SBTSP = INT(SBAN/0.6979)
    SS = 64
    KK = 91
    DAYS(W,GG,GGP,TGG,TG1,SS,KK)
    %cycle I = 64,1,91
       TR = 8
       %if W(I)<1 %then ->DR9
       %if AC>=STC-0.1 %then ->DR16
       %if STC-AC<8*RC %then ->CU16
       AC = AC+TR*RC
       ->DR9
CU16: X = STC-AC
       AC = STC
       TR = TR-X/RC
DR16: %if I<78-SBTSP %then ->DR9
       %if AD>=STD-0.1 %then ->DR9
       %if STD-AD<8*RD %then ->DR26
       AD = AD+TR*RD
       SB(P,0) = TR*RD
       SB(P,1) = I
       P = P+1
       ->DR9
DR26: X = STD-AD
       SB(P,0) = X
       SB(P,1) = I
       AD = STD
DR9: %repeat
   AP = 0
   STP = 0
```

```
   STS = L(4)
   STPL = L(4)
   AS = 0
   APL = 0
   P = 1
   PAN = STPL/(8*RPL)
   PAN = PAN/2
   PTSP = INT(PAN/0.7781)
   SS = 92
   KK = 140
   DAYS(W,HH,HHP,THH,TH1,SS,KK)
%CYCLE I=SS,1,KK
      TR = 8
%IF W(I)<1 %THEN ->DR10
      %if AS>=STS-0.1 %then ->PLA1
      %if STS-AS<8*RS %then ->ST1
      AS = AS+TR*RS
      ->DR10
ST1:  X = STS-AS
      AS = STS
      TR = TR-X/RS
PLA1: %if I<104-PTSP %then ->DR10
      %if APL>=STPL-0.1 %then ->DR10
      %if STPL-APL<8*RPL %then ->PLA2
      APL = APL+TR*RPL
      PH(P,0) = TR*RPL
      PH(P,1) = I
      P = P+1
      ->DR10
PLA2: X = STPL-APL
      PH(P,0) = X
      PH(P,1) = I
      APL = STPL
DR10: %repeat
   SS = 141
   KK = 217
   DAYS(W,II,IIP,TII,TI1,SS,KK)
   %if NY<=100 %then ->YEAR
PRINTSTRING("SUMMARY OF 100 YEARS RESULTS")
NEWLINE
PRINTSTRING("ANNUAL LOSSES")
   NEWLINE
   PRINTSTRING("YEAR    WWHEAT  WBARLEY  SBARLEY  POTATOES")
   NEWLINE
   %cycle I = 0,1,100
WRITE(I,2)
SPACES(2)
      %cycle J = 1,1,4
         PRINT(RES(I,J),4,2)
SPACE
      %repeat
      NEWLINE
   %repeat
%end %of %program
```

APPENDIX G

Summary of 100 years crop losses for different solutions

Summary of 100 years results of annual losses
for four crops

Year	WWheat	WBarley	SBarley	Potato
1	8.21	37.93	13.48	57.47
2	8.48	44.73	14.29	89.94
3	11.16	28.24	7.63	35.40
4	7.80	24.90	20.82	42.33
5	8.59	21.41	7.73	39.96
6	8.12	18.22	8.00	61.45
7	15.84	18.03	7.62	27.34
8	35.47	18.52	7.60	26.12
9	22.43	22.25	7.75	59.00
10	7.17	25.65	7.60	62.24
11	8.52	30.03	7.60	72.73
12	15.25	63.78	8.21	47.76
13	12.03	17.89	7.67	54.51
14	12.56	23.70	7.60	55.75
15	11.24	22.76	14.19	47.56
16	7.70	19.40	7.65	147.82
17	7.19	18.64	8.24	49.28
18	7.17	17.87	8.41	80.48
19	9.83	58.54	7.67	77.13
20	8.90	193.22	8.48	70.15
21	11.90	32.60	7.97	98.11
22	9.64	16.32	7.71	60.24
23	12.24	21.10	8.19	56.23
24	7.64	28.33	7.77	70.15
25	9.61	22.72	8.30	28.46
26	16.69	32.17	7.73	68.05
27	12.63	22.02	14.02	58.90
28	16.03	22.38	7.31	50.23
29	7.17	41.13	18.50	49.28
30	9.24	25.17	7.67	35.40
31	9.99	20.12	7.28	49.28
32	9.08	28.96	30.01	56.23
33	7.48	22.75	12.95	34.25
34	10.48	47.41	14.05	62.71
35	8.07	30.32	12.85	29.34
36	16.54	31.29	7.77	42.33
37	7.64	21.54	8.00	54.48
38	8.98	48.07	15.95	42.33
39	12.02	62.46	15.09	42.34
40	8.34	33.58	12.61	72.09
41	7.41	53.34	9.36	51.00
42	9.28	27.51	8.26	37.81
43	20.16	19.37	7.32	137.08
44	9.35	21.08	8.23	49.28
45	8.26	31.88	8.11	46.13
46	16.89	19.66	9.28	46.82
47	12.82	37.07	8.07	29.70
48	8.93	17.67	9.53	63.19
49	7.76	40.01	10.48	34.82
50	15.06	27.09	9.01	57.35
51	15.12	58.43	7.63	45.57
52	8.37	18.77	35.00	59.75
53	7.26	19.54	10.00	49.94
54	7.24	29.43	7.71	56.23
55	12.70	21.09	16.30	54.51
56	11.34	18.68	7.75	101.66
57	7.96	20.91	8.70	56.23
58	17.23	88.87	7.84	31.71
59	12.55	17.96	13.68	113.37

Year	WWheat	WBarley	SBarley	Potato
60	13.62	40.35	16.36	62.80
61	13.20	24.26	33.89	27.23
62	7.17	42.27	21.98	53.08
63	8.02	35.83	9.49	55.90
64	15.94	22.53	28.65	62.76
65	7.90	37.00	11.58	112.14
66	7.21	25.92	9.32	118.31
67	8.65	88.41	7.60	42.33
68	8.37	33.72	7.97	77.13
69	10.13	23.23	12.62	69.10
70	12.75	20.92	7.67	82.39
71	9.83	42.65	7.71	79.71
72	7.98	22.93	18.36	66.53
73	10.68	26.79	8.18	62.03
74	11.56	19.62	7.84	29.70
75	24.88	63.42	9.07	49.28
76	8.43	47.75	7.60	26.67
77	7.80	17.95	7.36	30.55
78	13.86	17.18	9.84	138.16
79	12.45	65.42	32.47	121.65
80	9.63	26.51	9.34	29.79
81	16.89	96.12	16.30	68.22
82	9.79	20.16	25.69	101.05
83	7.24	22.40	8.66	26.12
84	12.79	25.97	12.14	72.06
85	8.26	17.08	7.02	33.89
86	8.96	16.12	7.73	36.54
87	11.99	17.54	9.27	114.93
88	10.05	23.75	10.49	29.70
89	11.51	101.32	35.53	269.85
90	12.17	24.87	9.61	55.84
91	12.18	27.80	8.71	45.85
92	11.07	34.68	8.39	91.11
93	11.78	29.47	8.91	42.33
94	15.88	34.21	7.60	26.12
95	11.99	39.11	8.12	44.23
96	11.84	18.98	11.77	49.28
97	12.48	35.52	9.68	26.12
98	18.46	32.29	10.18	47.09
99	15.14	29.63	7.84	140.30
100	7.17	19.02	9.38	56.23

Summary of 100 years results of annual losses for four crops

Year	WWheat	WBarley	SBarley	Potato
1	7.91	30.50	13.28	57.47
2	7.22	43.02	14.25	89.94
3	11.05	25.74	7.58	35.40
4	7.71	23.96	20.76	42.34
5	8.49	21.07	7.71	39.96
6	7.51	17.84	7.95	61.45
7	14.34	19.11	7.53	27.34
8	35.03	19.47	7.58	26.12
9	21.09	21.64	7.70	59.00
10	7.13	24.61	7.58	62.24
11	8.28	28.85	7.58	72.73
12	15.15	62.97	8.11	47.76
13	11.84	18.49	7.63	54.51
14	11.33	23.23	7.58	55.75
15	10.74	22.00	14.09	47.56
16	7.61	19.82	7.58	147.82
17	7.13	18.14	8.16	49.28
18	7.13	16.17	8.33	80.48
19	9.78	47.96	7.63	77.13
20	8.72	134.41	8.41	70.15
21	11.52	28.05	7.87	98.11
22	9.32	17.54	7.68	60.24
23	11.93	20.61	8.13	56.23
24	7.54	25.13	7.71	70.15
25	9.43	22.16	8.17	28.46
26	15.41	26.71	7.71	68.05
27	12.50	21.65	13.96	58.90
28	15.85	21.98	7.26	50.23
29	7.13	40.60	18.45	49.28
30	8.88	22.99	7.58	35.40
31	9.92	19.82	7.12	49.28
32	9.02	27.28	29.99	56.23
33	7.37	22.44	12.52	34.25
34	9.21	33.60	13.86	62.71
35	8.01	32.70	12.75	29.34
36	14.46	26.21	7.71	42.33
37	7.51	21.22	7.87	54.48
38	8.87	34.10	15.88	42.34
39	11.95	48.55	14.98	42.34
40	7.13	29.04	12.54	72.09
41	7.33	41.87	9.33	51.00
42	9.21	26.67	8.20	37.81
43	20.02	16.21	7.29	137.08
44	9.17	21.34	8.17	49.28
45	8.08	25.18	7.98	46.13
46	16.74	18.87	9.21	46.82
47	12.45	32.32	8.02	29.70
48	8.87	18.81	9.32	63.18
49	7.59	34.56	10.32	34.82
50	13.82	24.68	8.95	57.35
51	12.41	44.76	7.58	45.57
52	8.33	17.89	34.94	59.75
53	7.13	19.13	9.58	49.94
54	7.13	26.23	7.68	56.23
55	12.52	20.82	16.23	54.51
56	11.28	17.88	7.70	101.66
57	7.85	20.65	8.58	56.23
58	17.12	35.93	7.80	31.71
59	12.49	17.47	13.41	113.37

Year	WWheat	WBarley	SBarley	Potato
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60	13.47	33.61	16.33	62.80
61	12.87	22.75	33.77	27.23
62	7.13	37.33	21.97	53.08
63	7.74	34.32	9.46	55.91
64	14.85	20.27	27.86	62.76
65	7.83	37.28	11.55	112.14
66	7.13	21.27	8.95	118.31
67	8.55	88.12	7.58	42.34
68	8.33	31.84	7.87	77.13
69	9.85	23.88	12.55	69.10
70	10.43	19.01	7.58	82.39
71	9.67	41.06	7.68	79.71
72	7.91	24.22	18.34	66.53
73	10.59	25.14	8.12	62.02
74	11.05	21.03	7.80	29.70
75	23.18	33.50	8.95	49.28
76	8.36	37.88	7.58	26.67
77	7.59	17.54	7.29	30.55
78	12.98	18.38	9.74	138.16
79	9.54	43.59	32.36	121.65
80	8.30	21.12	9.23	29.79
81	16.74	90.91	16.26	68.22
82	9.71	19.60	25.57	101.05
83	7.13	22.16	8.57	26.12
84	12.62	21.27	12.08	72.06
85	7.91	15.50	6.99	33.89
86	8.72	15.58	7.71	36.54
87	11.95	17.18	9.24	114.93
88	9.70	19.42	9.74	29.70
89	11.39	99.42	35.46	269.85
90	11.80	20.21	9.38	55.84
91	10.92	29.02	8.58	45.85
92	10.52	29.27	8.23	91.11
93	9.79	25.88	8.46	42.33
94	15.75	32.90	7.58	26.12
95	11.95	37.66	8.04	44.23
96	10.43	20.42	11.02	49.28
97	12.11	35.98	9.63	26.12
98	17.36	25.50	10.12	47.09
99	15.06	24.84	7.80	140.29
100	7.13	18.45	9.24	56.23

Summary of 100 years results of annual losses for four crops

Year	WWheat	WBarley	SBarley	Potato
1	7.66	30.04	13.12	57.47
2	7.18	38.75	14.23	89.94
3	10.99	25.21	7.57	35.40
4	7.65	23.13	20.72	42.33
5	8.41	20.80	7.69	39.96
6	7.47	17.51	7.92	61.45
7	14.21	18.57	7.49	27.34
8	34.80	18.96	7.57	26.12
9	21.00	21.41	7.67	59.00
10	7.10	23.69	7.57	62.24
11	8.24	27.80	7.57	72.73
12	15.11	62.23	8.03	47.76
13	11.74	18.32	7.61	54.51
14	10.58	22.85	7.57	55.75
15	9.52	21.51	14.03	47.56
16	7.54	19.72	7.57	147.82
17	7.10	17.69	8.12	49.28
18	7.10	17.18	8.28	80.48
19	9.76	39.78	7.61	77.13
20	8.62	75.66	8.36	70.15
21	11.37	27.85	7.86	98.11
22	9.04	17.18	7.66	60.24
23	11.86	20.46	8.09	56.23
24	7.46	24.85	7.69	70.15
25	9.35	21.69	8.07	28.46
26	14.24	25.80	7.69	68.05
27	12.40	21.43	13.91	58.90
28	15.80	21.74	7.23	50.23
29	7.10	40.36	18.42	49.28
30	8.57	21.25	7.57	35.40
31	9.88	19.72	7.11	49.28
32	9.00	26.28	29.98	56.23
33	7.35	22.19	12.49	34.25
34	9.18	32.49	13.70	62.71
35	7.98	32.06	12.67	29.34
36	14.35	21.76	7.69	42.33
37	7.47	20.95	7.86	54.48
38	8.79	33.75	15.84	42.33
39	11.93	48.24	14.90	42.33
40	7.10	25.13	12.50	72.09
41	7.27	40.55	9.32	51.01
42	9.18	25.94	8.17	37.81
43	19.95	17.29	7.27	137.08
44	9.11	20.68	8.14	49.28
45	7.98	25.05	7.89	46.13
46	16.65	18.61	9.18	46.82
47	12.13	31.92	8.00	29.70
48	8.84	18.34	9.29	63.19
49	7.48	33.94	10.19	34.82
50	12.99	22.98	8.92	57.35
51	12.30	44.49	7.57	45.57
52	8.31	17.56	34.92	59.75
53	7.10	18.77	9.21	49.94
54	7.10	25.08	7.66	56.23
55	12.38	20.60	16.19	54.51
56	11.25	17.24	7.67	101.66
57	7.76	20.49	8.52	56.23
58	17.04	32.30	7.78	31.71
59	12.46	17.04	13.39	113.37

Year	WWheat	WBarley	SBarley	Potato
60	13.37	33.36	16.31	62.80
61	12.60	22.37	33.69	27.23
62	7.10	37.19	21.97	53.08
63	7.65	33.81	9.45	55.91
64	14.50	19.66	27.82	62.76
65	7.78	36.92	11.53	112.14
66	7.10	20.96	8.92	118.31
67	8.48	78.50	7.57	42.33
68	8.31	30.87	7.86	77.13
69	9.80	23.18	12.51	69.10
70	10.37	20.26	7.57	82.39
71	9.55	39.65	7.66	79.71
72	7.87	23.92	18.33	66.53
73	10.54	23.77	8.07	62.03
74	10.99	20.83	7.78	29.70
75	23.13	32.17	8.92	49.28
76	8.31	37.74	7.57	26.67
77	7.48	17.18	7.27	30.55
78	12.45	17.95	9.70	138.16
79	9.52	43.45	32.35	121.65
80	8.21	20.80	9.14	29.79
81	16.65	83.33	16.23	68.22
82	9.68	19.10	25.50	101.05
83	7.10	21.79	8.50	26.12
84	12.49	17.27	12.04	72.06
85	7.87	15.22	6.98	33.89
86	8.68	15.26	7.69	36.54
87	11.93	16.90	9.23	114.93
88	9.58	19.32	9.72	29.70
89	11.30	84.78	35.41	269.85
90	11.74	18.66	9.27	55.84
91	10.89	27.83	8.48	45.85
92	10.47	25.00	8.09	91.11
93	9.49	25.22	8.42	42.33
94	15.64	27.04	7.57	26.12
95	11.93	36.38	7.99	44.23
96	10.37	20.24	10.84	49.28
97	11.83	32.69	9.61	26.12
98	16.35	25.22	10.07	47.09
99	15.02	23.27	7.78	140.30
100	7.10	17.95	9.23	56.23

Summary of 100 years results of annual losses
for four crops

Year	WWheat	Wbarley	SBarley	Potato
1	8.21	37.93	13.48	57.47
2	8.48	44.73	14.29	89.94
3	11.16	28.24	7.63	35.40
4	7.80	24.90	20.82	42.33
5	8.59	21.41	7.73	39.96
6	8.12	18.22	8.00	61.45
7	15.84	18.03	7.62	27.34
8	35.47	18.52	7.60	26.12
9	22.43	22.25	7.75	59.00
10	7.17	25.65	7.60	62.24
11	8.52	30.03	7.60	72.73
12	15.25	71.72	8.21	47.76
13	12.03	17.97	7.67	54.51
14	12.56	23.70	7.60	55.75
15	11.24	22.76	14.19	47.56
16	7.70	19.22	7.65	147.82
17	7.19	18.64	8.24	49.28
18	7.17	17.87	8.41	80.48
19	9.83	58.54	7.67	77.13
20	8.90	193.22	8.48	70.15
21	11.90	32.60	7.97	98.11
22	9.64	16.32	7.71	60.24
23	12.24	21.10	8.19	56.23
24	7.64	28.33	7.77	70.15
25	9.61	22.72	8.30	28.46
26	16.69	32.17	7.73	68.05
27	12.63	22.02	14.02	58.90
28	16.03	22.38	7.31	50.23
29	7.17	41.13	18.50	49.28
30	9.24	25.17	7.67	35.40
31	9.99	20.12	7.28	49.28
32	9.08	29.00	30.01	56.23
33	7.48	22.75	12.95	34.25
34	10.48	47.43	14.05	62.71
35	8.07	37.04	12.85	29.34
36	16.54	31.29	7.77	42.33
37	7.64	21.54	8.00	54.48
38	8.98	48.07	15.95	42.33
39	12.02	62.46	15.09	42.34
40	8.34	33.58	12.61	72.09
41	7.41	53.34	9.36	51.00
42	9.28	27.51	8.26	37.81
43	20.16	19.37	7.32	137.08
44	9.35	21.08	8.23	49.28
45	8.26	31.88	8.11	46.13
46	16.89	19.85	9.28	46.82
47	12.82	37.07	8.07	29.70
48	8.93	17.67	9.53	63.19
49	7.76	40.01	10.48	34.82
50	15.06	31.24	9.01	57.35
51	15.12	58.43	7.63	45.57
52	8.37	18.77	35.00	59.75
53	7.26	19.54	10.00	49.94
54	7.24	29.43	7.71	56.23
55	12.70	21.09	16.30	54.51
56	11.34	18.68	7.75	101.66
57	7.96	20.91	8.70	56.23
58	17.23	88.87	7.84	31.71
59	12.55	17.96	13.68	113.37

Year	WWheat	Wbarley	SBarley	Potato
60	13.62	40.41	16.36	62.80
61	13.20	24.26	33.89	27.23
62	7.17	42.27	21.98	53.08
63	8.02	35.83	9.49	55.90
64	15.94	22.53	28.65	62.76
65	7.90	37.00	11.58	112.14
66	7.21	25.92	9.32	118.31
67	8.65	93.44	7.60	42.33
68	8.37	33.72	7.97	77.13
69	10.13	23.23	12.62	69.10
70	12.75	20:92	7.67	82.39
71	9.83	42.65	7.71	79.71
72	7.98	22.93	18.36	66.53
73	10.68	26.79	8.18	62.03
74	11.56	19.62	7.84	29.70
75	24.88	63.42	9.07	49.28
76	8.43	47.75	7.60	26.67
77	7.80	17.95	7.36	30.55
78	13.86	17.18	9.84	138.16
79	12.45	65.42	32.47	121.65
80	9.63	26.51	9.34	29.79
81	16.89	96.12	16.30	68.22
82	9.79	20.16	25.69	101.05
83	7.24	22.25	8.66	26.12
84	12.79	25.97	12.14	72.06
85	8.26	17.08	7.02	33.89
86	8.96	16.12	7.73	36.54
87	11.99	17.54	9.27	114.93
88	10.05	23.75	10.49	29.70
89	11.51	101.46	35.53	269.85
90	12.17	24.87	9.61	55.84
91	12.18	34.57	8.71	45.85
92	11.07	34.68	8.39	91.11
93	11.78	29.69	8.91	42.33
94	21.53	43.83	7.60	26.12
95	11.99	39.11	8.12	44.23
96	11.84	18.98	11.77	49.28
97	12.48	37.95	9.68	26.12
98	18.46	32.29	10.18	47.09
99	15.14	29.63	7.84	140.30
100	7.17	19.02	9.38	56.23

Summary of 100 years results of annual losses
for four crops

Year	WWheat	WBarley	SBarley	Potato
1	7.98	40.61	16.85	75.70
2	9.46	45.51	13.86	105.68
3	12.12	30.81	8.09	49.83
4	7.57	22.59	20.38	57.40
5	8.36	19.10	8.20	55.79
6	7.89	15.90	8.46	77.69
7	15.61	17.71	7.19	38.57
8	36.44	18.20	8.06	39.81
9	22.20	19.95	8.21	77.67
10	6.93	23.34	8.06	82.32
11	8.29	27.72	8.06	88.65
12	17.20	76.53	8.67	69.35
13	11.80	17.33	8.13	70.38
14	13.53	21.39	8.06	73.02
15	12.22	20.46	13.76	68.57
16	7.47	17.65	8.11	175.26
17	6.96	16.32	8.70	63.74
18	6.93	20.48	8.87	104.54
19	9.60	64.55	8.13	91.67
20	8.67	190.44	8.94	88.40
21	11.67	35.30	8.43	112.70
22	9.41	16.00	8.17	80.31
23	12.01	18.79	8.65	70.71
24	7.41	32.20	8.23	85.29
25	8.92	20.41	8.76	42.48
26	16.47	34.83	8.20	84.67
27	13.60	19.71	13.58	85.89
28	15.80	20.82	8.75	66.73
29	6.93	49.02	20.01	63.74
30	9.02	22.84	8.13	51.12
31	10.97	17.81	6.85	63.74
32	7.92	27.26	29.56	70.71
33	7.25	20.45	12.52	48.84
34	11.45	55.92	13.62	80.00
35	7.84	36.24	12.42	40.57
36	16.31	34.00	8.23	56.78
37	7.41	19.24	8.46	72.98
38	8.29	69.67	15.51	56.78
39	11.78	80.33	14.65	56.78
40	8.11	36.27	15.18	96.34
41	8.39	59.67	8.93	71.03
42	10.25	26.06	8.72	57.67
43	21.15	23.93	8.80	157.98
44	9.12	20.75	8.69	63.74
45	8.03	39.73	8.57	63.38
46	16.67	20.02	9.31	67.64
47	13.79	39.75	8.53	42.89
48	8.70	17.35	9.99	77.69
49	7.53	42.90	10.05	52.65
50	17.66	32.48	9.47	74.64
51	16.83	74.37	8.09	61.41
52	8.14	16.45	34.54	77.02
53	8.23	18.08	10.45	69.99
54	7.01	27.59	8.17	70.71
55	12.48	18.78	15.86	70.38
56	12.31	16.35	8.21	119.05
57	8.94	18.61	9.16	70.71
58	18.46	91.47	8.30	55.57
59	12.31	15.63	11.53	144.89

Year	WWheat	WBarley	SBarley	Potato
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60	12.47	42.20	15.92	77.69
61	11.59	25.71	33.44	39.86
62	6.93	45.14	29.00	70.35
63	7.79	31.69	9.09	70.71
64	15.72	25.12	28.20	89.60
65	7.67	43.46	11.15	126.76
66	6.98	28.59	9.78	146.19
67	7.95	95.86	8.06	56.78
68	8.14	31.43	6.97	94.26
69	9.90	22.91	10.91	84.67
70	12.06	23.99	8.13	98.33
71	9.60	40.37	8.17	95.65
72	7.75	22.62	17.91	86.63
73	9.06	24.47	8.64	77.69
74	11.34	19.31	8.30	42.89
75	25.86	83.11	9.53	63.74
76	7.74	54.12	8.06	37.91
77	7.57	15.62	6.93	42.89
78	13.64	16.86	10.30	154.99
79	13.43	104.82	32.01	139.13
80	9.40	29.62	9.80	43.82
81	16.67	98.53	15.86	84.67
82	9.56	17.84	25.25	127.65
83	7.01	20.17	9.12	35.96
84	13.76	28.65	11.71	87.98
85	9.23	19.69	8.49	46.52
86	8.72	15.47	8.20	49.17
87	11.76	15.22	8.84	133.79
88	9.82	26.38	10.06	42.89
89	13.70	110.01	35.07	710.85
90	22.13	27.50	10.07	70.71
91	11.95	37.00	9.17	63.08
92	10.84	37.37	8.85	105.68
93	11.55	37.57	9.37	56.78
94	14.26	40.96	8.06	35.96
95	11.76	38.39	8.58	60.08
96	11.61	18.67	12.22	63.74
97	12.25	34.87	9.28	35.96
98	18.24	40.60	9.75	68.68
99	16.12	32.25	8.30	154.99
100	6.93	16.70	8.95	70.71

Summary of 100 years results of annual losses
for four crops

YEAR	WWheat	WBarley	SBarley	Potato
1	7.91	30.50	13.28	57.47
2	7.22	43.02	14.25	89.94
3	11.05	25.74	7.58	35.40
4	7.71	23.96	20.76	42.34
5	8.49	21.07	7.71	39.96
6	7.51	17.84	7.95	61.45
7	14.34	19.11	7.53	27.34
8	35.03	19.47	7.58	26.12
9	21.09	21.64	7.70	59.00
10	7.13	24.61	7.58	62.24
11	8.28	28.85	7.58	72.73
12	15.15	62.97	8.11	47.76
13	11.84	18.64	7.63	54.51
14	11.33	23.23	7.58	55.75
15	10.74	22.00	14.09	47.56
16	7.61	19.82	7.58	147.82
17	7.13	18.14	8.16	49.28
18	7.13	16.17	8.33	80.48
19	9.78	47.96	7.63	77.13
20	8.72	134.41	8.41	70.15
21	11.52	28.05	7.87	98.11
22	9.32	17.54	7.68	60.24
23	11.93	20.61	8.13	56.23
24	7.54	25.13	7.71	70.15
25	9.43	22.16	8.17	28.46
26	15.41	26.71	7.71	68.05
27	12.50	21.65	13.96	58.90
28	15.85	21.98	7.26	50.23
29	7.13	40.60	18.45	49.28
30	8.88	22.99	7.58	35.40
31	9.92	19.82	7.12	49.28
32	9.02	27.28	29.99	56.23
33	7.37	22.44	12.52	34.25
34	9.21	33.60	13.86	62.71
35	8.01	32.50	12.75	29.34
36	14.46	26.21	7.71	42.33
37	7.51	21.22	7.87	54.48
38	8.87	34.10	15.88	42.34
39	11.95	48.55	14.98	42.34
40	7.13	29.04	12.54	72.09
41	7.33	41.87	9.33	51.00
42	9.21	26.67	8.20	37.81
43	20.02	16.21	7.29	137.08
44	9.17	21.34	8.17	49.28
45	8.08	25.18	7.98	46.13
46	16.74	18.93	9.21	46.82
47	12.45	32.32	8.02	29.70
48	8.87	18.81	9.32	63.18
49	7.59	34.56	10.32	34.82
50	13.82	24.40	8.95	57.35
51	12.41	44.76	7.58	45.57
52	8.33	17.89	34.94	59.75
53	7.13	19.13	9.58	49.94
54	7.13	26.23	7.68	56.23
55	12.52	20.82	16.23	54.51
56	11.28	17.88	7.70	101.66
57	7.85	20.65	8.58	56.23
58	17.12	35.93	7.80	31.71
59	12.49	17.47	13.41	113.37

Year	WWheat	WBarley	SBarley	Potato
60	13.47	33.61	16.33	62.80
61	12.87	22.75	33.77	27.23
62	7.13	37.33	21.97	53.08
63	7.74	34.32	9.46	55.91
64	14.85	20.27	27.86	62.76
65	7.83	37.28	11.55	112.14
66	7.13	21.27	8.95	118.31
67	8.55	78.76	7.58	42.34
68	8.33	31.84	7.87	77.13
69	9.85	23.88	12.55	69.10
70	10.43	19.01	7.58	82.39
71	9.67	41.06	7.68	79.71
72	7.91	24.22	18.34	66.53
73	10.59	25.14	8.12	62.02
74	11.05	21.03	7.80	29.70
75	23.18	33.50	8.95	49.28
76	8.36	37.88	7.58	26.67
77	7.59	17.54	7.29	30.55
78	12.98	18.38	9.74	138.16
79	9.54	43.59	32.36	121.65
80	8.30	21.12	9.23	29.79
81	16.74	84.51	16.26	68.22
82	9.71	19.60	25.57	101.05
83	7.13	22.16	8.57	26.12
84	12.62	21.27	12.08	72.06
85	7.91	15.50	6.99	33.89
86	8.72	15.58	7.71	36.54
87	11.95	17.18	9.24	114.93
88	9.70	19.42	9.74	29.70
89	11.39	85.81	35.46	269.85
90	11.80	20.21	9.38	55.84
91	10.92	28.73	8.58	45.85
92	10.52	29.27	8.23	91.11
93	9.79	25.69	8.46	42.33
94	15.75	32.90	7.58	26.12
95	11.95	37.66	8.04	44.23
96	10.43	20.42	11.02	49.28
97	12.11	35.19	9.63	26.12
98	17.36	25.50	10.12	47.09
99	15.06	24.84	7.80	140.29
100	7.13	18.45	9.24	56.23

Summary of 100 years results of annual losses for four crops

Year	WWheat	WBarley	SBarley	Potato
1	7.66	30.04	13.12	57.47
2	7.18	41.60	14.23	89.94
3	10.99	25.21	7.57	35.40
4	7.65	23.13	20.72	42.33
5	8.41	20.80	7.69	39.96
6	7.47	17.51	7.92	61.45
7	14.21	18.57	7.49	27.34
8	34.80	18.96	7.57	26.12
9	21.00	21.41	7.67	59.00
10	7.10	23.69	7.57	62.24
11	8.24	27.80	7.57	72.73
12	15.11	62.23	8.03	47.76
13	11.74	18.32	7.61	54.51
14	10.58	22.85	7.57	55.75
15	9.52	21.51	14.03	47.56
16	7.54	19.72	7.57	147.82
17	7.10	17.69	8.12	49.28
18	7.10	15.77	8.28	80.48
19	9.76	46.30	7.61	77.13
20	8.62	75.66	8.36	70.15
21	11.37	27.85	7.86	98.11
22	9.04	17.18	7.66	60.24
23	11.86	20.46	8.09	56.23
24	7.46	24.55	7.69	70.15
25	9.35	21.69	8.07	28.46
26	14.24	25.80	7.69	68.05
27	12.40	21.43	13.91	58.90
28	15.80	21.74	7.23	50.23
29	7.10	40.36	18.42	49.28
30	8.57	21.25	7.57	35.40
31	9.88	19.72	7.11	49.28
32	9.00	26.28	29.98	56.23
33	7.35	22.19	12.49	34.25
34	9.18	32.49	13.70	62.71
35	7.98	32.06	12.67	29.34
36	14.35	25.50	7.69	42.33
37	7.47	20.95	7.86	54.48
38	8.79	33.75	15.84	42.33
39	11.93	48.24	14.90	42.33
40	7.10	28.85	12.50	72.09
41	7.27	40.55	9.32	51.01
42	9.18	25.94	8.17	37.81
43	19.95	15.88	7.27	137.08
44	9.11	20.68	8.14	49.28
45	7.98	25.05	7.89	46.13
46	16.65	18.61	9.18	46.82
47	12.13	31.92	8.00	29.70
48	8.84	18.34	9.29	63.19
49	7.48	33.94	10.19	34.82
50	12.99	22.98	8.92	57.35
51	12.30	44.49	7.57	45.57
52	8.31	17.56	34.92	59.75
53	7.10	18.77	9.21	49.94
54	7.10	25.41	7.66	56.23
55	12.38	20.60	16.19	54.51
56	11.25	17.24	7.67	101.66
57	7.76	20.49	8.52	56.23
58	17.04	33.38	7.78	31.71
59	12.46	17.04	13.39	113.37

Year	WWheat	WBarley	SBarley	Potato
60	13.37	33.36	16.31	62.80
61	12.60	22.37	33.69	27.23
62	7.10	37.19	21.97	53.08
63	7.65	33.81	9.45	55.91
64	14.50	19.66	27.82	62.76
65	7.78	36.92	11.53	112.14
66	7.10	20.96	8.92	118.31
67	8.48	78.50	7.57	42.33
68	8.31	30.87	7.86	77.13
69	9.80	23.18	12.51	69.10
70	10.37	18.86	7.57	82.39
71	9.55	39.65	7.66	79.71
72	7.87	23.92	18.33	66.53
73	10.54	23.77	8.07	62.03
74	10.99	20.83	7.78	29.70
75	23.13	32.17	8.92	49.28
76	8.31	37.74	7.57	26.67
77	7.48	17.18	7.27	30.55
78	12.45	17.95	9.70	138.16
79	9.52	43.45	32.35	121.65
80	8.21	20.80	9.14	29.79
81	16.65	89.03	16.23	68.22
82	9.68	19.10	25.50	101.05
83	7.10	21.79	8.50	26.12
84	12.49	20.96	12.04	72.06
85	7.87	15.22	6.98	33.89
86	8.68	15.26	7.69	36.54
87	11.93	16.90	9.23	114.93
88	9.58	19.32	9.72	29.70
89	11.30	98.11	35.41	269.85
90	11.74	19.81	9.27	55.84
91	10.89	27.83	8.48	45.85
92	10.47	28.73	8.09	91.11
93	9.49	25.22	8.42	42.33
94	15.64	32.74	7.57	26.12
95	11.93	36.38	7.99	44.23
96	10.37	20.24	10.84	49.28
97	11.83	35.94	9.61	26.12
98	16.35	25.22	10.07	47.09
99	15.02	24.40	7.78	140.30
100	7.10	17.95	9.23	56.23

Summary of 100 years results of annual losses for four crops

Year	WWheat	WBarley	SBarley	Potato
1	7.68	35.67	16.64	75.70
2	8.19	43.67	13.82	105.68
3	10.82	25.43	8.04	49.83
4	7.48	21.65	20.31	57.40
5	8.26	18.76	8.17	55.79
6	7.28	15.51	8.41	77.69
7	15.29	16.78	7.10	38.57
8	36.01	17.14	8.04	39.81
9	22.08	19.33	8.16	77.67
10	6.89	22.31	8.04	82.32
11	8.05	26.54	8.04	88.65
12	14.92	66.66	8.57	69.35
13	11.61	16.47	8.09	70.38
14	11.11	20.93	8.04	73.02
15	10.51	19.69	13.65	68.58
16	7.38	17.51	8.04	175.26
17	6.89	15.81	8.62	63.74
18	6.89	15.52	8.79	104.54
19	9.55	45.26	8.09	91.66
20	8.49	131.85	8.87	88.40
21	11.29	30.72	8.33	112.70
22	9.09	15.22	8.14	80.31
23	11.70	18.30	8.59	70.71
24	7.31	23.69	8.17	85.29
25	8.74	19.85	8.63	42.48
26	15.19	29.34	8.17	84.67
27	13.47	19.35	13.52	85.89
28	15.62	20.42	8.69	66.73
29	6.89	48.50	19.97	63.74
30	8.65	20.66	8.04	51.12
31	10.90	17.51	6.69	63.74
32	7.86	25.31	29.54	70.71
33	7.14	20.13	12.09	48.84
34	10.19	39.23	13.43	80.00
35	7.78	37.11	12.32	40.57
36	16.17	24.60	8.17	56.78
37	7.28	18.91	8.33	72.98
38	8.18	40.21	15.44	56.78
39	11.72	56.13	14.54	56.78
40	6.89	27.43	15.10	96.34
41	7.10	46.07	8.90	71.03
42	10.19	25.22	8.66	57.67
43	21.01	15.56	8.76	157.98
44	8.94	19.02	8.63	63.74
45	7.85	28.44	8.44	63.38
46	16.51	17.52	9.24	67.64
47	13.42	34.97	8.49	42.89
48	8.64	16.49	9.78	77.69
49	7.36	37.31	9.89	52.65
50	13.59	26.75	9.41	74.64
51	13.39	54.39	8.04	61.41
52	8.10	15.56	34.49	77.02
53	6.89	17.67	10.04	69.99
54	6.89	23.63	8.14	70.71
55	12.29	18.51	15.80	70.38
56	12.26	15.56	8.16	119.05
57	7.62	18.34	9.04	70.71
58	16.89	34.41	8.26	55.57
59	12.26	15.15	11.26	144.89

Year	WWheat	WBarley	SBarley	Potato
60	12.32	36.30	15.89	77.69
61	11.27	21.38	33.32	39.86
62	6.89	40.06	28.97	70.35
63	7.51	30.61	9.06	70.71
64	14.63	19.97	27.41	89.60
65	7.59	43.96	11.11	126.76
66	6.89	23.91	9.41	146.19
67	7.86	90.52	8.04	56.78
68	8.10	29.55	6.87	94.26
69	9.62	21.57	10.85	84.67
70	11.87	18.37	8.04	98.33
71	9.44	38.78	8.14	95.65
72	7.68	21.91	17.89	86.63
73	8.97	22.83	8.58	77.69
74	10.82	18.72	8.26	42.89
75	24.17	25.14	9.41	63.74
76	7.66	42.14	8.04	37.91
77	7.36	15.22	6.86	42.89
78	12.75	16.05	10.19	154.99
79	10.51	48.34	31.90	139.13
80	9.27	23.71	9.69	43.82
81	16.51	93.29	15.82	84.67
82	9.48	17.27	25.12	127.65
83	6.89	19.85	9.02	35.96
84	13.59	19.68	11.65	87.98
85	7.68	15.18	8.47	46.52
86	8.49	14.94	8.17	49.17
87	11.72	14.86	8.81	133.79
88	9.47	22.02	9.31	42.89
89	12.36	104.47	35.00	710.85
90	21.76	18.64	9.84	70.71
91	11.90	31.12	9.04	63.08
92	10.29	27.66	8.69	105.68
93	10.76	24.33	8.92	56.78
94	14.12	29.64	8.04	35.96
95	11.72	36.95	8.50	60.08
96	11.40	18.11	11.47	63.74
97	11.88	42.78	9.23	35.96
98	17.14	27.61	9.69	68.68
99	16.04	23.28	8.26	154.99
100	6.89	16.13	8.81	70.71